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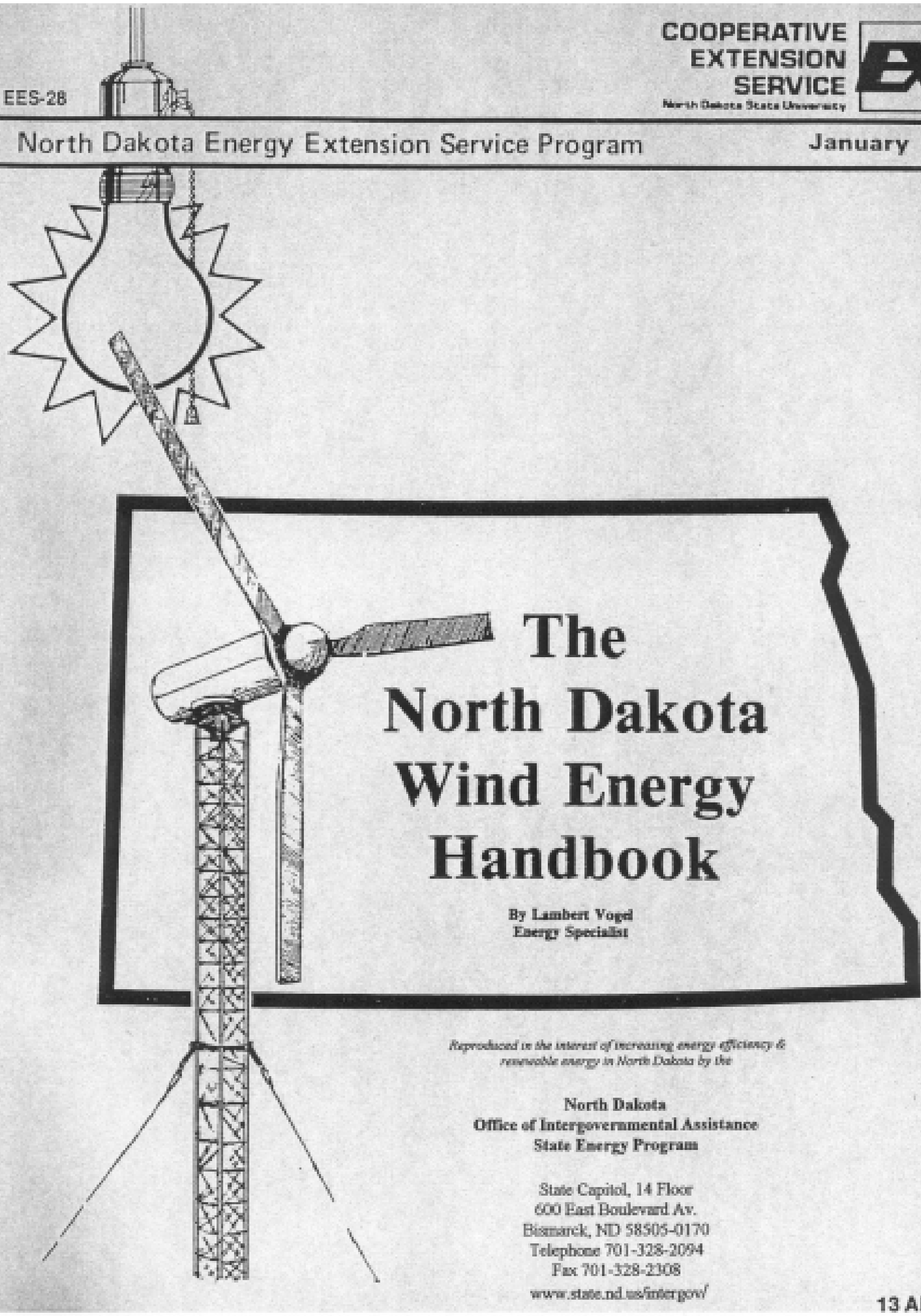

The North Dakota Wind Energy Handbook

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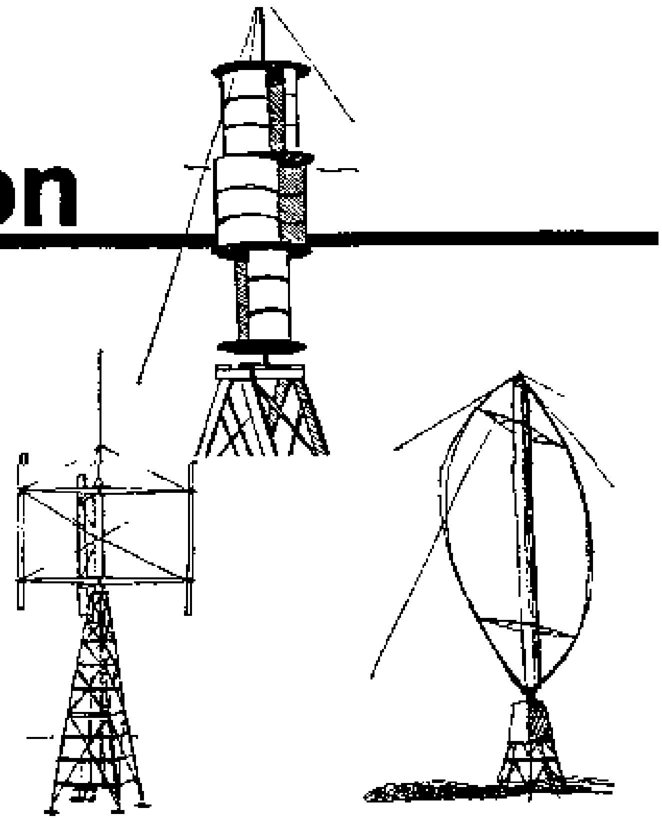
Introduction



Wind is a real source of energy in North Dakota. Windmills have been used to pump water for many years. When electricity became generally available, locally significant amounts were generated by wind-driven generators.

Only with the advent of suburban and rural electrification did the utility of wind power decline. Yet, while some machines vanished, others — and the wind — are still here.

Now, today's higher energy prices have revitalized interest in wind power. In an era of finite fuel sources, wind is recognized as a renewable energy resource which can be tapped in many places.

Water Pumping Windmills

Windmills converting wind to reciprocating mechanical energy to pump water have been the most successful and familiar application of wind power. Even today, thousands of them, in varying stages of repair, are sprinkled over the landscape.

Then as now, the most difficult aspect of designing a wind machine was **not** getting it to work, but rather getting it to hold together. Fortunately, the continual need for water created an expanding market for wind-powered water pumpers and stimulated a number of inventions and patents on ways to get mechanical energy from the wind.

Daniel Halliday created the first widely successful design in 1854.

Halliday's hinged rotor was constructed of a number of wooden slats, fastened by hinges to a steel ring. As the rotational velocity of the rotor increased, flyweights on the inner portion of the blades pushed them parallel to the wind, shaping the rotor like a bottomless basket.

Unfortunately, the hinged rotor, though effective, had a relatively large number of moving joints and pivots which tended to be a maintenance problem.

Other inventors experimented with and developed a "solid" rotor windmill, with blades firmly fastened to a hoop.

Speed control was managed by offsetting the center of the wind wheel from the tower top and using a vane-and-spring arrangement to turn the wheel sideways to the wind if conditions warranted. Because of its simpler construction, this new design became the industry standard and is still being produced.

Between 1880 and 1935, an estimated 6½ million windmills were sold in the United States. Strong sales continued until the 1950s. During their peak use in the 1930s, these mills produced energy equivalent to 1 billion kWh per year.

The completion of rural electrification programs and the low electricity prices of the 1960s contributed to the decline of water-pumping windmills. Electric motors were less expensive to operate and less fickle than wind-driven pumps. By the late 1970s, only two major manufacturers of water-pumping windmills were still in business.

Electrical Generating Windmills

In 1860, Moses Farmer patented a device he thought had tremendous sales potential. His invention, which converted wind power into electricity, was viewed as an interesting novelty.

Unfortunately, the world had no use for electricity in 1860; and Farmer's novelty was 50 years ahead of the time when a general market for its product would appear.

In 1882, the world's first electric utility began operating in London. A few months later, parts of New York City were electrified. The Edison Electric Illuminating Company, Topeka, Kansas, was organized in 1885. When it went into operation in 1887, it had 110 customers.

In 1886, George Westinghouse and William Stanley demonstrated the practicality of long-distance transmission of electricity by use of alternating current (AC). Since cities had dense enough populations to pay for the distribution system, most urban areas enjoyed the convenience of electric power by the first decade of the twentieth century.

But, at that time it was very expensive to distribute power where users were far apart, and utility companies refused to extend their lines to serve lower population densities.

One response was the development of electric distribution cooperatives; another was the development of electricity-generating windmills. Both responses brought rural residents labor-saving electric motors, lights, and the luxury of radio.

Some of the first wind-generators were constructed by modifying existing water-pumping windmills. Although they were inefficient, the old windmills were easily obtainable and the required alterations were well within the ability of most machinists and farmers.

Experiences with different types of blades began to show two or three

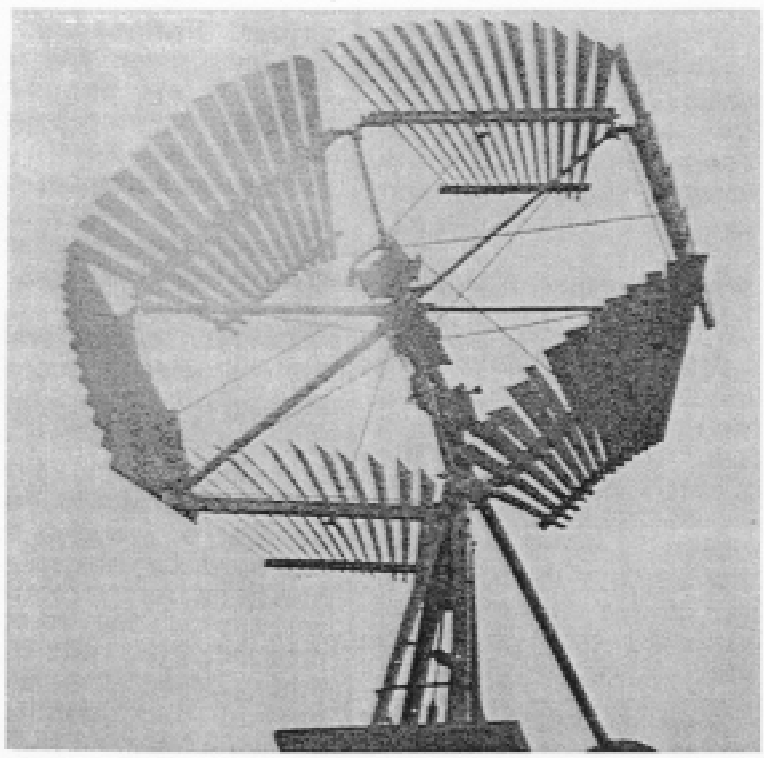


Figure 1. Halliday windmill out of sail. The first widely successful design, Daniel Halliday's hinged rotor was made of wooden slats fastened to a steel ring by hinges. As the rotational velocity increased, flyweights pushed the slats parallel to the wind, shaping the rotor like a bottomless basket.

blades with an aerodynamic shape rotating at high speed delivered more power for electrical generation.

With fewer blades, less material was needed for the same capacity, so the cost-per-watt was reduced. As a result, new types of wind generators began to replace the modified water pumpers.

All early wind-driven generators produced direct current (DC) electricity, and most relied on batteries for storage during calm spells. While typical generators were 32 volts, with a peak capacity of about 2,500 watts, experience with the real, sometimes hostile, environment led to many different modifications to extend lifetimes and reduce maintenance problems.

Although the generators were useful for lights and radios, their ability to drive devices requiring large amounts of power was limited.

In 1935, Congress, recognizing electricity's ability to increase farm productivity, established the Rural Electrification Administration (REA). Congress intended the REA to finance the local development of power distribution groups.

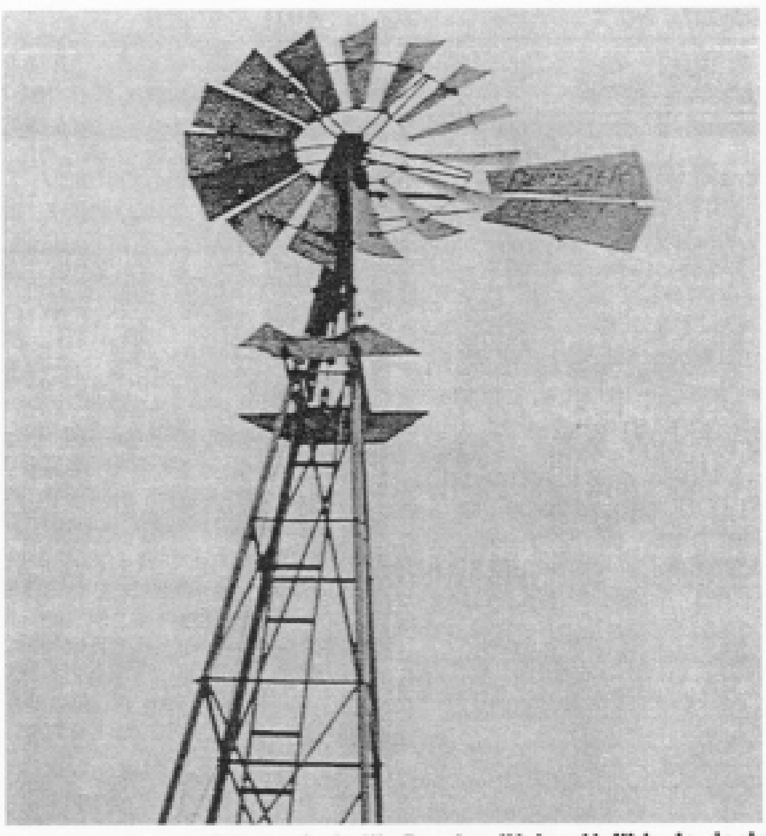


Figure 2. A solid rotor windmill. By simplifying Halliday's design, this type windmill quickly became the water-pumping industry's standard product, and is still common today.

After World War II, wind-driven generators were relegated to extremely remote locations, or to the few independents who refused to rely on anyone else for power. Even in rural areas, large central generation became the main source of electrical power.

Recently, however, new considerations have started affecting the generation of electricity. Constructing new and large central plants has become very expensive, and the farther a user is from the plant, the greater the line loss. Fuels are much more expensive and their use causes environmental consequences previously ignored.

To overcome these financial and environmental problems, two approaches are being considered. One is conservation and the prudent use of existing energy resources.

The other is a new look at renewable energy resources. Wind is one of these resources.

Glossary

Like any specific subject matter, "wind energy" has developed a specialized vocabulary. Wind energy specialists and researchers talk (and write) about torque, velocity, WECS and Ohms as casually as most of us discuss our daily wardrobe.

In order to aid you in using this handbook more effectively, the following glossary of common wind energy words has been compiled.

WECS: A common acronym for a wind-driven generator is WECS, (Wind Energy Conversion System) and the term will be used in this handbook. In other literature, the reader may find the term SWECS, (Small Wind Energy Conversion System). This second term is not necessary here since the smaller machines are the focus of this book.

ENGLISH (Metric): Units will be given in both English and metric values. Persons interested in wind systems become familiar with both systems, since needed information comes from a variety of sources, much of it gathered by others for other reasons. (For example, weather data gathered at airports is for air travel, not power production).

LINEAR MEASURE: Linear measure will be given in English units, as feet or miles, with the equivalent metric value given in parentheses. For example, 5 ft. (1.52 m), where "ft." stands for feet and "m" stands for meters. The continued reference to meters (10 m), is one exception to the English unit rule. Much wind data is gathered at this international height and restating the figure as 32.8 ft. (10 m) is awkward. For conversion:

Multiply feet by .3048 to obtain meters.

Multiply meters by 3.281 to obtain feet.

Divide feet by 5,280 to obtain miles.

VELOCITY: Velocities will be usually given in miles per hour, followed parenthetically by meters per second, or mi/hr (m/s). Sometimes, velocity will be given as feet per second, i.e., fps. Occasionally, velocity will be given as knots. For conversion:

Multiply mi/hr by .4470 to obtain m/s.

Multiply m/s by 2.237 to obtain mi/hr.

Multiply m/s by 3.281 to obtain fps.

Multiply mi/hr by 1.467 to obtain fps.

Multiply knots by 1.15 to obtain mi/hr.

WATTS: Units of electrical power are watts. It's the rate at which work is done, or energy transformed. This unit gives the electrical demand of an appliance or the capacity of an electrical generator. A kilowatt (kW) is 1,000 watts (1000 W) and a MegaWatt (MW) is a million watts, or 1,000 kilowatts. Some examples of the electrical demands for appliances and the production capabilities of generators are:

100 W Light Bulb	100 W
Color TV Set	200 W
Central Air Conditioner	5.0 kW
Electric Range (all burners and oven on)	12 kW
Electric Clothes Dryer	5.5 kW
Bicycle Generator	3 W
Automobile Generator	1 kW
Contemporary Central Electric Plant	500 to 1500 MW

The average electrical power demand for a house with gas or other non-electric heat is about 1 kW.

Remember, this average value will vary greatly. During the day, if cooking and clothes drying are being done at the same time, the demand would be 10 to 15 kW. However, during the night the demand might drop as low as the few watts needed to keep clocks running. For an all-electric house, the demand would usually be higher, perhaps 1.5 kW on the average.

The WECS considered here have sizes ranging from about 1-200 kW. The smallest would have blades about 5 ft. (1.5 m) long; the largest blades would be about 50 ft. (15.2 m) long. For power density conversions: **divide W/m2 by 10.76 to obtain W/ft2.**

Since both are measures of work, watts can be "converted" to horsepower, and vice versa. **Multiply hp by 746 to obtain watts. Divide watts by 746 to obtain hp.**

Volts: Voltage is "pressure" or the electromotive force along a conductor. ("E" in the formula used in this book.)

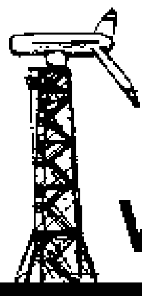
Amperes: Ampere is a measure of the quantity of electricity flowing, or current. ("I" in the formula used in this book.)

Ohms: Ohm is the resistance, or opposition, to the flow of electrical current. "R" in the formula: **$E = I \times R$: Volts = Amperes x Ohms**

kWh: Energy is measured in kilowatt hours (kWh), the use of one kW for one hour. For example, the clothes dryer listed above would use 5.5 kWh of energy if it were run for one hour.

A monthly utility bill from the electric utility will list the number of kWh used during the billing period. The typical house with a 1 kW average demand uses 720 kWh per month. Identifying the monthly use of electric energy (in kWh) is an important element in the selection of a WECS.

Torque: Torque is the force making, or trying to make, something rotate. Measured as foot-pounds, it's the force of one pound pushing one foot from the center of rotation, say a one-pound force one foot out from an axle.



Chapter One: Wind Machines

Three types of energy are commonly derived from wind-driven machines: mechanical, electrical and thermal.

Farm water-pumping windmills are good examples of mechanical systems. The Wind Energy Conversion Systems (WECS) which electrified farms before rural electrification illustrate the electricity production. And, more recently, wind machines directly converting wind energy to heat have been made.

The smaller electricity-producing WECS are the machines to be analyzed in this book. A wide variety of wind machines types and styles exists.

Typically, a wind-driven-generator system has six important components or sub-systems.

A rotor, turned by the wind, takes energy from the wind. A transmission may be used to match the rotor's speed to that needed by the generator. A generator converts rotational energy into electricity.

A speed or power control limits power at higher wind speeds and "turns off" the rotor when wind speeds are too high for safe operation or too low for efficient operation. A tower is required to safely anchor the rotor in the windstream. And, finally, there's the electrical distribution system, with its switches and means of using (or storing) the electricity produced. While other features may be present on a particular wind-driven machine, all WECS share these common elements.

The Rotor

The rotor transforms the wind's energy into rotational energy in a spinning shaft. The area swept by the rotor determines how much power can be extracted from the wind.

For instance, the two-bladed rotor shown in Figure 3 has a blade diameter of 12 ft. (3.66 m), and thus a swept area of 113 ft^2 (10.5 m^2). Chapter two's calculations shows that, with a 25 mi/hr wind speed, there are 78.4 watts in each square foot area (843.6 W/m^2). So at 25 mi/hr, there are about 8.86 kW of power in 113 ft^2 (10.5 m^2).

A "perfect" rotor could convert 59 percent of this power into mechanical energy, or 5.25 kW. (Beyond this 59.3 percent limit derived from aerodynamic theory, there would be no "wind" behind the rotor, and it would stop.)

A "practical" rotor might convert on the average only about 25 percent of the available energy. Continuing the example, 8.86 kW x 25 percent = 2.22 kW. A 25 mi/hr wind speed (11.2 m/s) is a common rating point for a WECS, so it would be reasonable to market this machine as a 2 kW WECS. Remember: a WECS' output rating must include the rating windspeed.

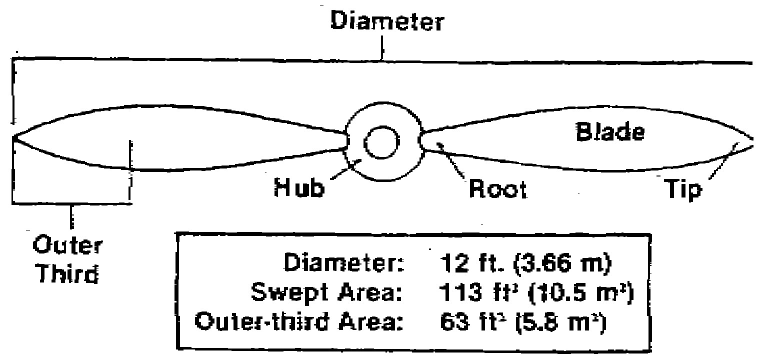
Table 1 lists output power for a range of wind speeds and rotor sizes. The table's values were calculated assuming the rotor could extract 25 percent of the wind's power.

Rotors are designed to be most efficient at a particular wind speed, and don't work as well at other wind speeds. The table is approximate and a specific rotor might obtain more or less power than that shown. The table illustrates the general way in which increasing rotor diameter increases output (in the same wind), or how increasing wind-speed increases power from the same rotor.

Lift or Drag

A rotor may be classified as either a lift- or a drag-type device.

Figure 3. Rotor Nomenclature.



The lift-type rotor will employ a member with an airfoil cross-section, creating low pressure on one side of the blade to draw it forward. A drag-type rotor's blade, however, is merely pushed by the wind's force. Its aerodynamic efficiency is extremely low. (See Figure 4)

Of the two types, the lift rotor is the most efficient in terms of power, and is better suited for electricity generation. For mechanical application, a drag rotor at low speeds may be the best choice, since it usually provides better starting torque. The rotors for the calculations in Table 1 were assumed to be lift-types.

Horizontal or Vertical Axis

WECS rotors are also classified as having either a horizontal axis or a vertical axis. A horizontal-axis machine (HAWT for Horizontal Axis Wind Turbine) has its rotor shaft parallel to the earth's surface; a vertical-axis machine's rotor shaft (VAWT for Vertical Axis Wind Turbine) is at right angles to the earth's surface (See Figures 5 and 6).

HAWT

The horizontal-axis wind machine is the most familiar type. *Very efficient and* easily mounted on tall towers, they've been used for many years.

However, despite their apparent popularity, the machines do have some deficiencies. One "disadvantage" is the requirement of either mounting the generator on top of the tower, or devising some sort of right-angle transmission with a long shaft to a ground-level generator.

A second disadvantage is the necessity of aligning the machine with the wind either "*upwind*" or "*downwind*," as in Figures 7 and 8. A tail (or other mechanism) holds the rotor on the *tower's upwind side for* the first type, while wind pressure blows the rotor to the tower's downwind side for the second type.

VAWT

In contrast to the HAWT, the vertical-axis machine can accept the wind from any direction, and its generator can be located at the base of the rotor, close to the ground. The "disadvantage" of the VAWT is that it tends to be a little less efficient than its horizontal-axis counterpart.

There are three common vertical-axis machines: the Darrieus, The Giromill and the Savonius.

Darrieus blades (Figure 9) are curved in the shape of a spinning rope or troposkien; this natural shape reduces the stress in the blades.

The Giromill (Figure 10) has straight blades to improve the rotor's efficiency, and the blade pitch angle varies as the blades rotate.

The Savonius is a drag device, a favorite for simple applications. It can be easily constructed by splitting an oil drum in half and offsetting the halves about a vertical axis. A Savonius machine with more aerodynmamically sophisticated rotors than split oil drums can be built.

Figure 4. Rotor Cross Sections.

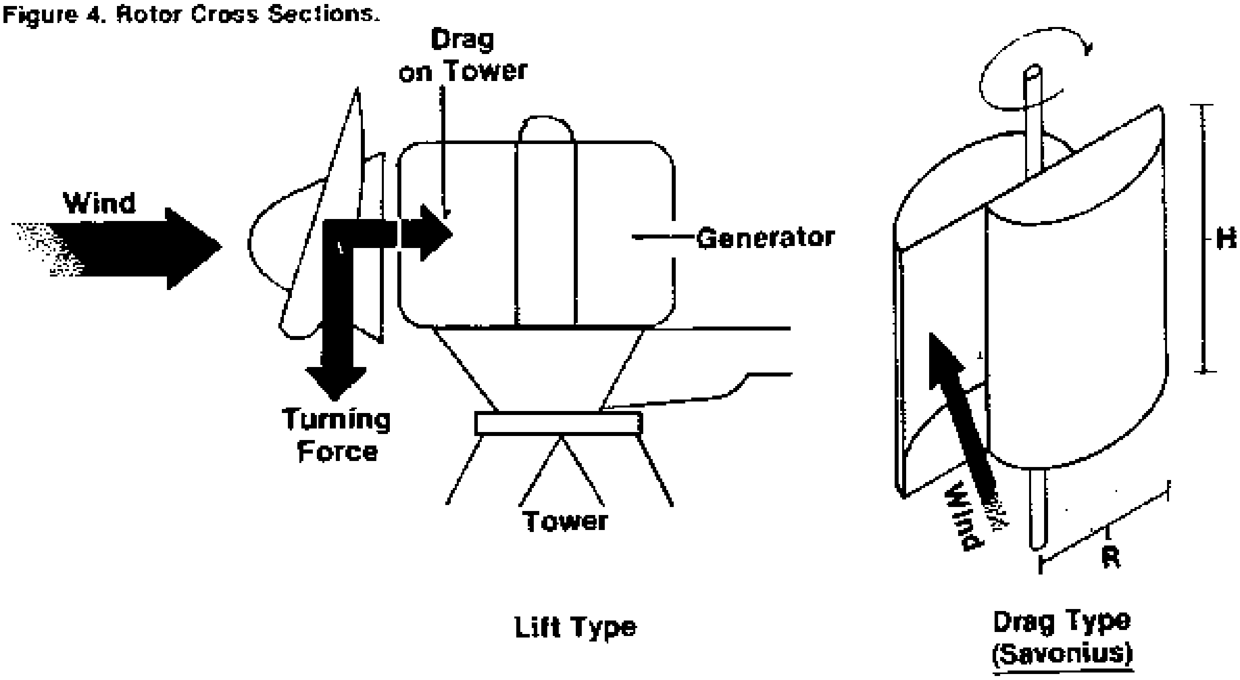


Table 1. Estimated WECS Power Output (in kW at 25% rotor efficiency)

Wind Speed (mi/hr)	Rotor diameter in feet						
	10	12	14	16	20	25	30
10	.09	.14	.18	.24	.38	.59	.84
15	.32	.46	.62	.81	1.3	2.0	2.8
20	.75	1.1	1.5	1.9	3.0	4.7	6.8
25	1.5	2.1	2.9	3.8	5.9	9.2	13
30	2.5	3.6	5.0	6.5	10	16	23
35	4.0	5.8	7.9	10	16	25	36

A wind machine needs to be mounted on a tower. Usually the rotor should be as high into the windstream as possible.

Because some vertical-axis WECS require guy wires from the top of the machine, mounting them is more difficult than mounting their horizontal-axis counterparts. Typically, vertical-axis machines require larger guyed areas, or more complicated support structures, than horizontal-axis machines.

Number of Blades

One or many blades may be used in a rotor. Aerodynamic theory indicates the fewer the blades, the more efficient the rotor.

A rotor with a single blade would be most efficient; however, one blade puts an unbalanced mechanical stress on the windmill and is seldom used.

A two-bladed rotor has better balance, but still produces torque fluctuations. These fluctuations can be reduced if three or more blades are used. The rotor costs a little more, but the WECS runs smoother and lasts longer.

A larger number of blades produces more starting torque, important in some applications. For example, the multi-bladed water-pumping windmill is not very aerodynamically efficient, but has good starting torque and can easily pump water when a two- or three-bladed rotor wouldn't start.

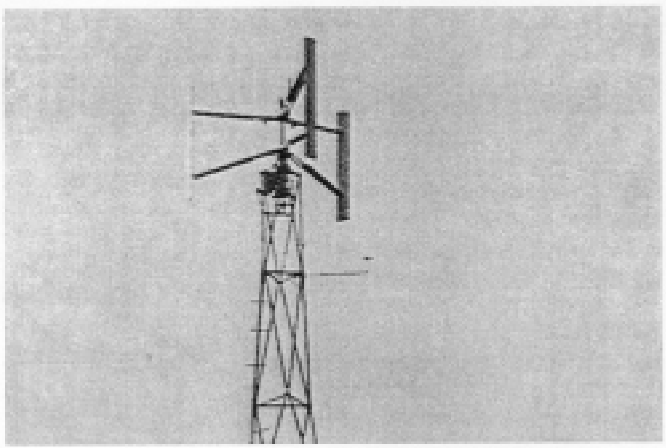


Figure 5. A VAWT. This WECS is an example of a vertical axis wind system. The system is known as vertical because its axis of rotation is perpendicular to the ground.

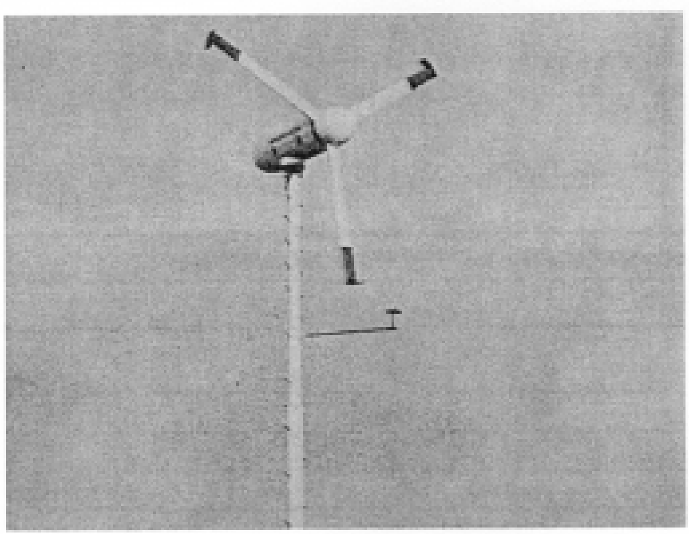


Figure 6. A HAWT. The wind system with a propellor-like rotor is known as a horizontal-axis system, because its generator shaft — the axis of rotation — is parallel to the horizon.

Blade pitch, the angle between the blade and the plane of rotation, is an important rotor characteristic. (See Figure 12)

For most rotor blade shapes with low pitch, efficiency will be high, but starting torque low. With a large pitch angle, the opposite is true.

Most WECS used to generate electricity don't need high starting torques, and use pitch angles of about 3 to 8 degrees.

A twisted blade has high

pitch near its root, or innermost part of the blade, and gradually changes to a low pitch at its tip. It's more efficient than a straight blade, and will produce more energy.

For applications where starting torque is important, the twisted blade produces more starting power than its straight counterpart.

However, the twisted blade is more difficult (and more costly) to manufacture, so in a trade-off between rotor efficiency and cost, many smaller WECS use straight blades.

The most productive portion of the horizontal-axis rotor is its outer one-third. As shown in Figure 3, this outer third sweeps over more than half (53%) the rotor area.

The inner two-thirds has a smaller area, and its performance is partially spoiled by the wind interference of the hub and generator housing.

For this reason, a HAWT with a straight blade and even a very poor airfoil shape near its root can be nearly as good as a very sophisticated rotor — if the simple rotor has a smooth airfoil, no wind interference and proper pitch angle over the outer part of the blade.

Some wind machines employ a mechanism to vary the pitch in response to wind speed. With pitch change, rotor efficiency can be slightly increased, but only at the price of additional cost and maintenance.

Reducing the rotor power output at high wind speeds to protect the machine is the real value of variable pitch. This subject is discussed more fully under speed and power controls.

Rotor/Generator Transmission

Aerodynamic theory dic-

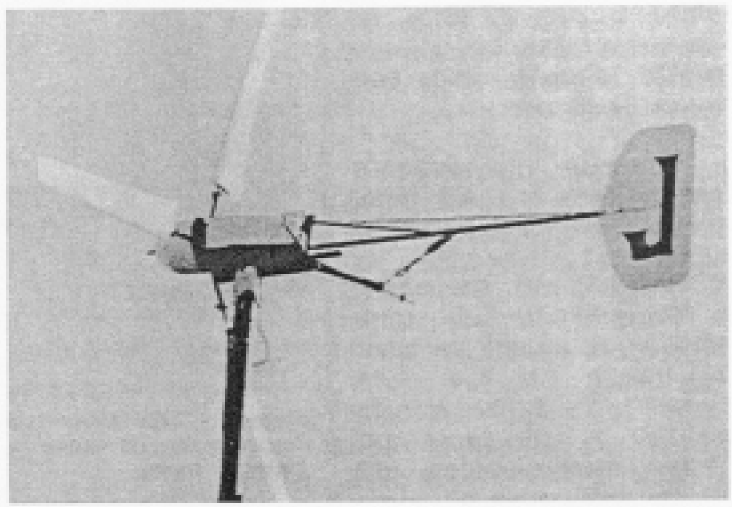


Figure 7. An upwind windmill. In an upwind design, the wind first passes over the rotor and then by the generator behind it. A tail vane acts like the rudder on a sailboat and keeps the rotor facing the wind. The tail vane may also be used to shut the plant off by folding at right angles to the generator.

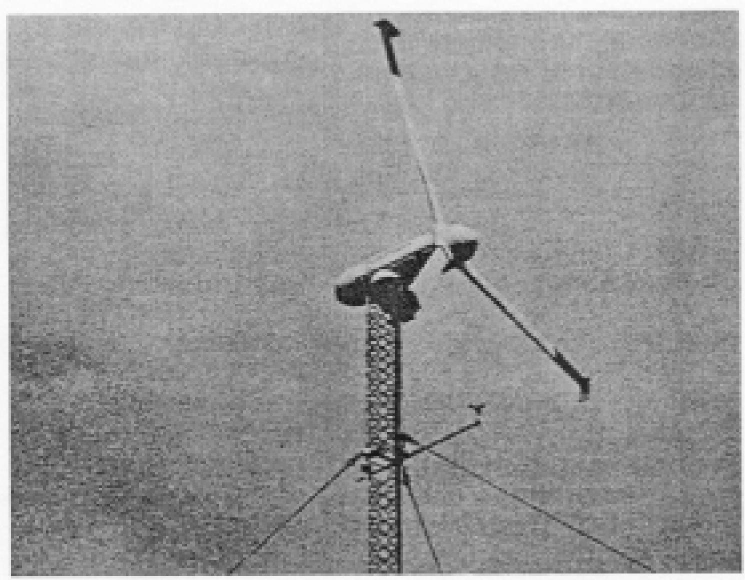


Figure 8. A down-wind windmill. In a down-wind design, the wind first passes over the generator and then the rotor. No tail vane is used, so a mechanical or electrical brake is needed to shut off the plant.

tates a rotor's tip should go through the air at about four to eight times the speed of the wind.

Thus, a 14 ft. (4.27 m) diameter rotor in a 25 mi/hr (11.2 m/s) wind should spin between 200-400 revolutions per minute (rpm), while a 200 ft. (61.0 m) diameter rotor on a large WECS should spin between 14-28 rpm.

However, generators (particularly the AC type) are usually designed to spin at speeds of 1,200-1,800 rpm. Therefore, a transmission of some kind must usually be used to match the low rotor speed to the higher speeds needed by the generator. These transmissions are an integral part of many WECS.

Some DC generators can run at low speeds and connect to the rotor without a transmission. This reduces the cost, complexity and maintenance requirements of the WECS.

Generators and the Electrical System

Electricity is used in one of two forms: alternating current (AC) or direct current (DC).

Most utilities produce AC electricity, while some industries and institutions and a few utilities use DC electricity. Transformers can easily change AC voltage, helping transmission from the utility to the power user, while DC voltage is more difficult to transform. While DC power can easily be stored in batteries, it's very difficult to store AC power.

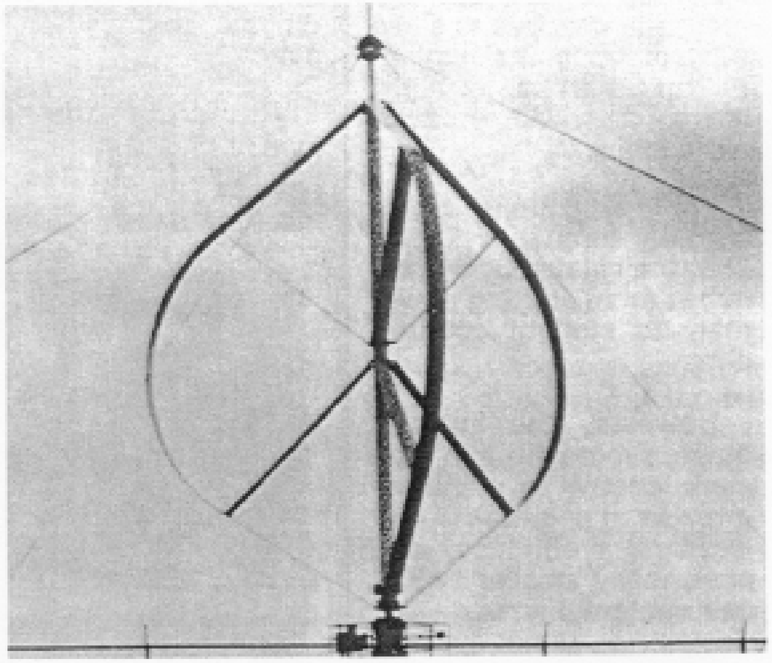


Figure 9. The Darrieus WECS. The blades of this vertical-axis wind machine are curved in the shape of a spinning rope or troposkien to reduce stress.

Wind generators are available to produce either AC or DC energy.

Stand-Alone or Parallel

A wind machine providing electricity can either stand alone or operate in parallel with central station power.

In a stand-alone system, there's no connection to the electric utility, and battery storage is usually required to provide energy during calm spells and for peak load conditions.

A parallel generating system typically draws some power from the utility to control the output, or when the windmill output is insufficient for the demand.

If the wind machine generates excess power, it may be sold to the utility. In effect, the utility grid becomes the "storage" for the wind-driven parallel generator; a WECS owner "deposits" excess electricity with the utility to be "drawn out" at a future time. The essential storage is the fuel not used at some generating plant when excess WECS electricity is fed back into the grid.

Stand-Alone

A stand-alone system is usually used where utility service is unavailable, or

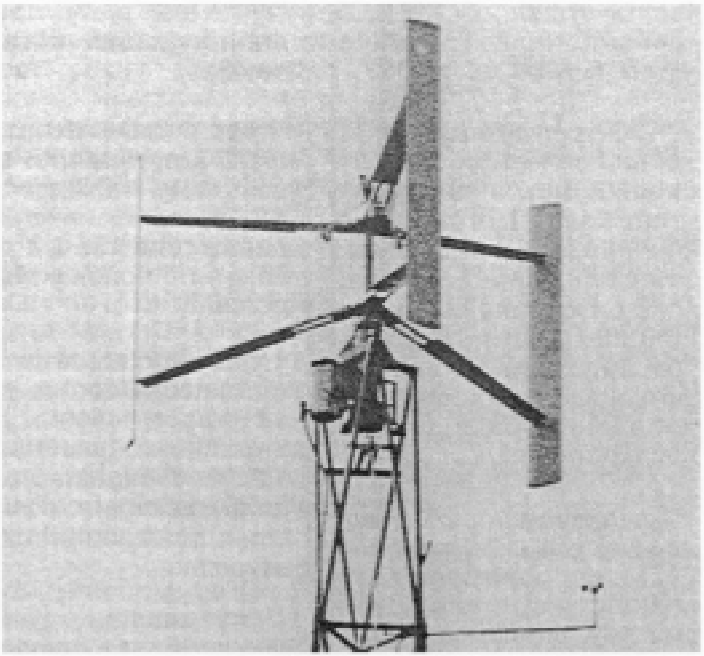


Figure 10. The Giromill WECS. This VAWT's straight blades improve the efficiency of its rotor. The blade pitch angle varies as the blades rotate.

where it's too expensive to run an electrical line to the location. It's usually economically impractical to make customers completely independent of their utilities if they already have the service. But, for some people, the value of independence from the electrical utility overcomes conventional economics.

A DC WECS (using either a DC generator or an AC generator with a rectifier) is used in most stand-alone systems, and batteries are installed for storage.

If all the electrical devices (lights, TV, etc.) at the location can run on DC, the wind system is complete. However, if AC is desired, an inverter is also installed to make the needed change.

Because batteries and, possibly, an inverter must be purchased in addition to the WECS, the stand-alone system is relatively expensive.

In addition, the storage and conversion process is somewhat inefficient, as some power is lost in the inverter if the DC-to-AC conversion is made.

The size of the WECS to be installed depends upon the average power demand at the location, the inverter efficiency and the wind characteristics.

Battery capacity depends upon the length of the calm spell the user wishes to get through without the loss of power, and/or the amount and cost of the back-up power production, such as from a diesel- or gas-engined generator.

These factors make specifying a stand-alone system rather difficult.

The best residential application is probably for a house specifically designed to use very little energy, such as an earth-sheltered home, or a well-insulated structure using natural daylighting and proper control of solar thermal gain. In such cases, less battery storage and wind machine capacity is needed.

In addition to its residential application, stand-alone functions include billboard lighting, remote transmitting stations and/or applications requiring DC electricity.

Parallel

Parallel generation is done in concert with electrical utility. If the wind generator isn't supplying enough power for the house or business where it's being used, the necessary extra power is drawn from the utility. If the wind generator is producing extra power, the excess is sent back to the utility.

This type storage is usually cheaper and more efficient (from the WECS owner's point of view) than batteries. It's the reason parallel generation is more attractive than an effort to maintain complete independence from the utility.

With parallel generation and the proper switching, output cables from the WECS connect directly into the home wiring system. The power always goes in the proper direction, either into the home system or back to the utility, and no expensive equipment is needed to direct the power on its way (aside from the switching, safety, meters and other operating requirements). **Always check with the electric power supplier prior to installing a WECS connected to the electric utility.**

AC/DC

Direct current is produced in the typical stand-alone system. The WECS generator in a parallel system may be AC or DC.

DC is converted to AC before connection to the utility. But, whether converted from DC or produced directly as AC, the parallel-generated power must be compatible with the utility. That is, it must be at the correct frequency and voltage to match that of the utility, and in phase or synchronous.

A synchronous inverter converts the DC power to AC, and automatically monitors the utility frequency to produce the correct frequency AC. The inverter's AC output can then be directly connected to the electrical system of the residence or business (with the proper safety, metering and switching devices).

Tests have demonstrated DC power, with a proper match between the WECS and the inverter, can be converted to AC power with an efficiency of 90-95 percent.

However, since an incorrect match can result in very poor efficiency, it's important to be certain the WECS is designed to run with a particular converter when purchasing this type of system.

For example, a WECS designed for a stand-alone application, won't necessarily run well with a synchronous inverter in parallel generation.

The advantages of the DC type of system are that its generator can be quite simple and its rotor can change speed in response to changes in wind speed. Disadvantages are the extra cost of the inverter and its "waste" of some power in the DC-AC conversion.

WECS with AC synchronous or induction generators have their outputs directly connected to the utility grid.

A synchronous generator is run at a controlled speed, so its output frequency matches the utility's. To begin operation, the generator must be brought to the proper speed and synchronized with the utility grid before it's electrically connected.

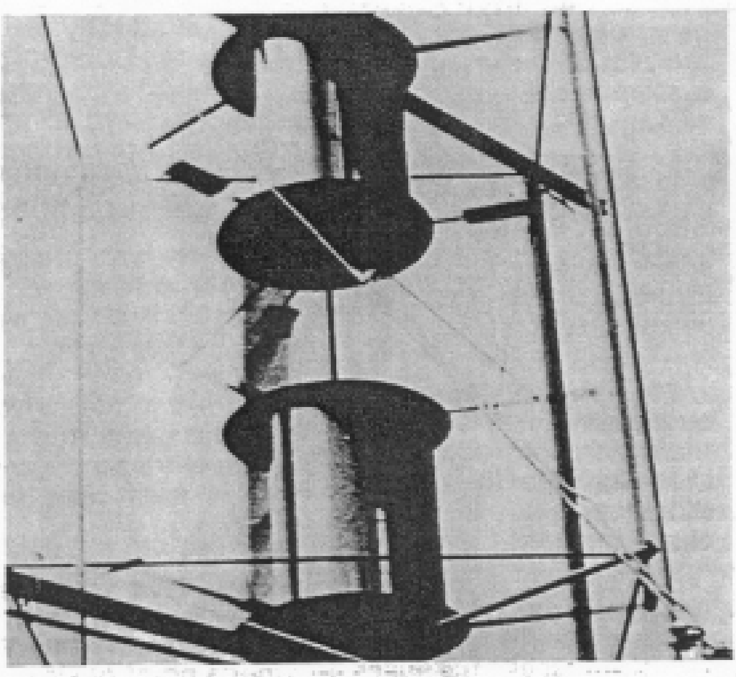


Figure 11. The Savonius WECS. The Savonius VAWT is a drag device, often favored for simple applications. While carefully crafted (and expensive) commercial models are available, a Savonius can also be made by splitting an oil drum and offsetting the halves about a vertical axis.

This requires a fairly sophisticated control system.

An induction generator can run as a motor, then become a generator when forced above its normal running speed. It always puts out the correct frequency, even though its rotational speed may vary slightly as wind speed changes.

For these reasons, the induction generator is the "popular" small WECS generator. Its control system is very simple; disconnect the system during light winds so it doesn't use "outside" energy by running as a motor.

Compared to the synchronous generator, the induction generator has the advantage of simplicity. However, its disadvantages include its inability to generate electricity of quite the same high quality (power factor) and a lower efficiency.

While at this time, the power factor isn't an issue for small wind-machines, the situation may well change if many units are installed on a particular utility system.

Electric power to a residence is usually single-phase, while power to a larger business or commercial institution is three-phase. The single-phase AC WECS are only available in less-than-25 kW sizes. Larger WECS may have three-phase outputs.

Speed and Power Control

A wind energy system's electrical output is limited by its generator's electrical capacity.

The term, "rated capacity," is used to specify the maximum power that can safely be generated without damaging the system. This rated output occurs at a specific wind speed and is usually called the rated wind-speed.

If no control is used when the wind exceeds the machine's rated wind-speed, its rotor may produce more power than its generator can handle and the generator will overheat.

The control mechanism prevents this damage. It also reduces the tendency for tower failure in high winds.

Changing the rotor pitch and turning the rotor out of the wind are two common control methods of reducing power at high wind-speeds.

Changing rotor pitch is used to reduce the rotor's performance. In high winds, the pitch angle is increased to lower rotor performance enough to prevent overloading the generator. When winds subside, the pitch returns to its normal high-performance angle. The pitch-changing mechanism can either be mechanical or electrical.

Turning the rotor out of the wind reduces power by reducing the rotor's effective sweep area. The rotor can be turned by displacing the rotor shaft from a pivot and holding the rotor in position with a spring. The wind force on the rotor works against this spring

Figure 12. Rotor Blade Pitch.

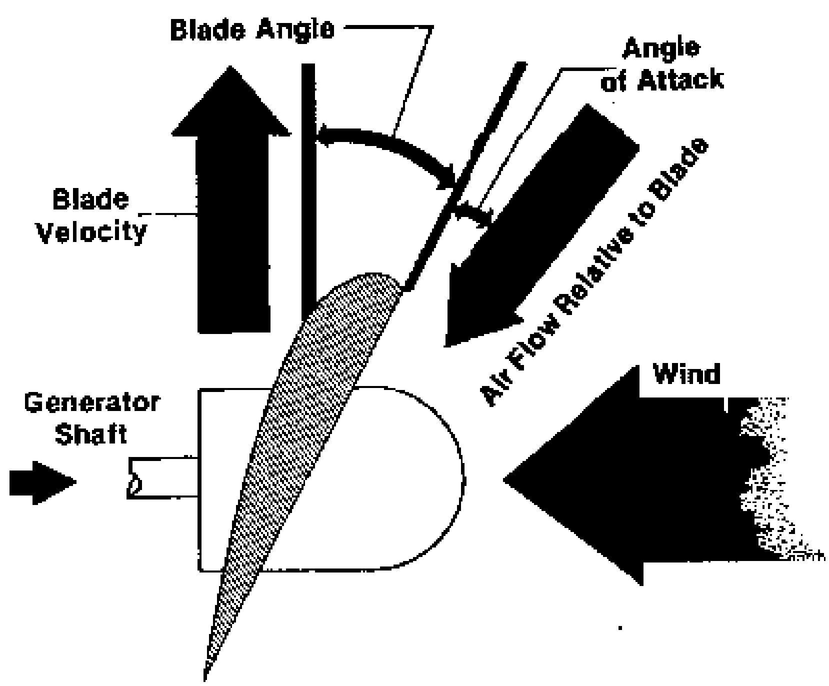


Figure 13. Free-standing WECS tower. Free-standing towers need no supporting guy wires, use little space and are usually more expensive than guyed towers. They can be constructed of steel (or wooden) poles or metal frameworks.

and, as wind speed increases, the force will increase and turn the rotor, reducing its projected area and power output.

Above a specified wind speed, called the cut-out speed, operation becomes too dangerous for many WECS, and the system must be shut down.

This can be done with an electrically activated brake, or the WECS can completely turn out of the wind. When the wind slows to safe operating speeds, normal operation is resumed.

Another type of WECS control unrelated to power control, is intended to keep the rotor from wildly spinning to destruction.

If a transmission shaft breaks, or the brake fails or utility power fails, the rotor no longer has its work load and will spin uncontrolled.

If rotor speeds increase beyond a safe design rate, the rotor can be completely destroyed.

In these cases, an aerodynamic brake on the rotor will protect it. A brake may change blade pitch or be a device on the blade back or tip which bends to add drag at overspeeds.

These backup devices provide almost fail-safe protection against severe damage to the whole WECS. Experience indicates it to be a worthwhile feature.

Towers

Wind speed increases with height. Therefore, it's desirable to place the wind generator as high as possible. Several tower types are available, all with a common characteristic: extra height increases cost.

Free-Standing or Guyed

There are two types of commonly available towers; free-standing and guyed. While the free-standing tower has no supporting guy wires, and uses less space, it's usually more expensive than guyed counterparts. Free-standing towers may be constructed from steel poles, such as used for large street lights, or from a metal framework typical of some radio and TV towers (Figure 13). Short free-standing towers can be made from wood, such as a wood utility pole.

Since a guyed tower is unable to withstand the wind by itself, one or more sets of guywires anchor it. The tower may be a steel pole, pipe, a metal framework, or wooden utility pole. The guy wires are usually steel cable.

In guyed-tower construction, the tower supports the wind machine's weight, while the guy wires provide resistance to sideways stress. (See Figure 14.)

While free-standing towers are used where space is limited, their guyed counterparts are usually employed where there's room around the tower to anchor the guy lines. In particular, the generally larged guyed-area of the vertical-axis WECS is an issue in siting this type of machine.

While towers made specifically for WECS are available, the choice depends partly on what's locally available and the overall economics.

Dangers

There are three instances in which a wind machine can be dangerous: when blades are thrown, when ice from the blades is thrown or when the tower collapses.

It's expected each WECS will be designed so its blades will never be lost. Ice buildup tends to slow the rotor and limit the ice throw radius. Waiting until the ice has cleared before resuming power production is a recommended operating procedure.

Correctly designing the tower minimizes the third danger. It must be capable of withstanding strong winds under two circumstances.

First, the tower must withstand wind pressure when the rotor is turning. A spinning rotor presents a large effective area to the wind, so a considerable sideways force is placed on the tower. The tower must withstand this force at the highest operating wind speed.

While the WECS may be shut down or turned out of the wind at higher wind speeds, the rotor, the WECS housing and the tower itself still present a considerable area.

The tower should at least withstand winds up to about 100 mi/hr (with the WECS in place, but shut down), although local building codes may specify different wind speeds.

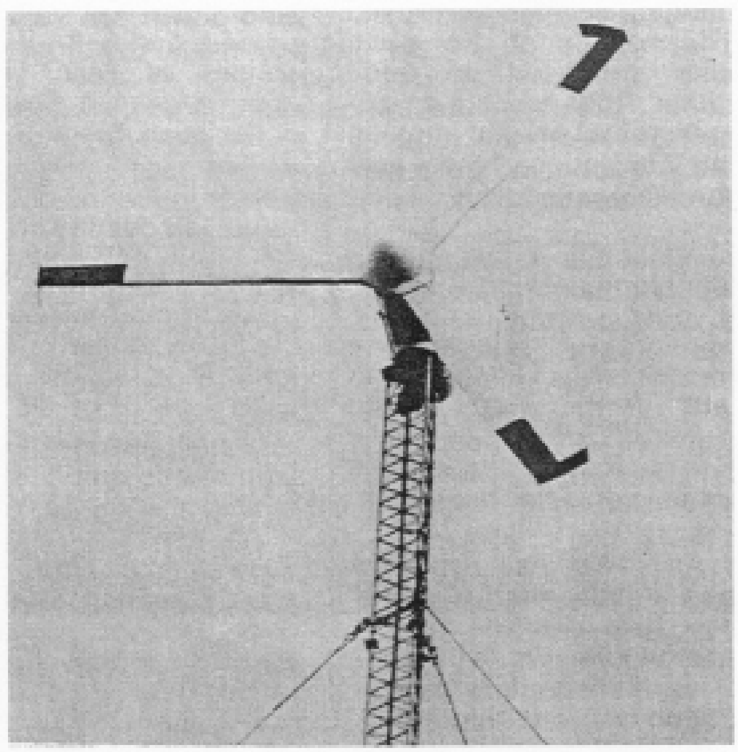
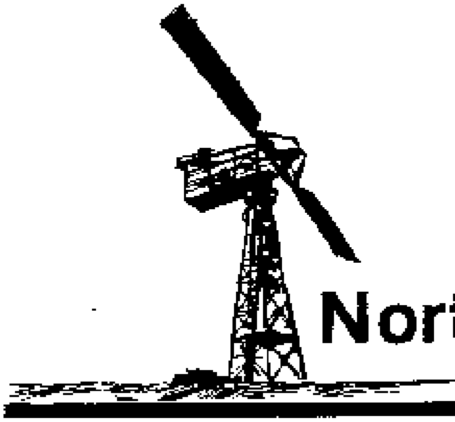


Figure 14. Guyed WECS tower. Guyed towers need one or more sets of guy wires to anchor themselves against the wind. While the tower may be a steel or wooden pole, metal framework or pipe, the guy wires are usually steel cable.



Chapter Two: North Dakota Winds

Atmospheric winds are the result of two separate forces.

Pressure gradients, produced by uneven solar heating, accelerate the air. The rotation of the earth also produces an additional, but separate, acceleration on the moving air. The action of these two forces creates wind.

While this explanation is simpler than wind analysis, it does provide the basic reason for atmospheric motion. The principal result of the winds is the transfer of atmospheric energy to offset the effects of uneven solar heating.

Any substance in motion has kinetic energy; some of the wind's kinetic energy can be extracted. The relationship describing power density per unit area in the wind is:

$$\text{Power} = \frac{\text{air density} \times \text{wind speed}^3}{2}$$

or, $P = (pV^3)/2$

Air density is determined by temperature and barometric pressure, both of which can change from day-to-day and with the wind generator site's elevation.

Air density and, thus, wind power can vary 10-15 percent during the year. Air density at 2,500 feet is about 8 percent less than at sea level. Since changes in wind speed have a much greater influence on power output, air density changes are often not considered when calculating wind power. Using the standard sea level density of .075 lb/ft^3 (1.20 kg/m^3) and a wind speed of 25 mi/hr (11.2 m/s), the power density (in metric units) is:

$$P = \frac{(1.20)(11.2)^3}{2}$$

$$= 843.6 \text{ Watts/Meter}^2$$

$$P = \frac{843}{10.76} = 78.35 \text{ Watts/Ft}^2$$

Thus, if the wind is blowing at 25 mi/hr, there are slightly more than 78 watts in each square foot of air perpendicular to the wind direction.

No wind machine can extract all this power. The theoretically "perfect" wind machine extracts only 59 percent of the total power; practical windmills only 15-40 percent.

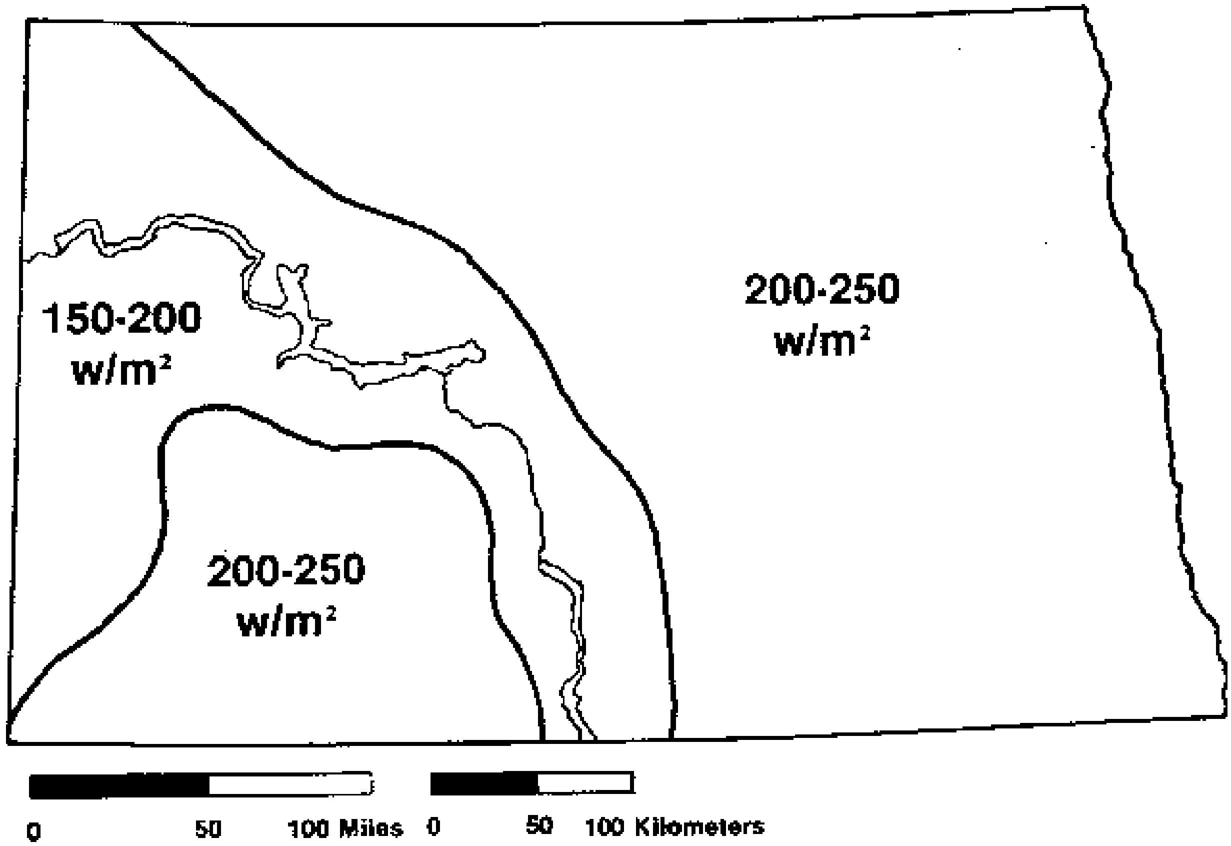
Both air density and wind speed contribute to the wind's power. In other words, the greater the air density, the greater the wind power; as wind speed increases, so does wind power.

Within North Dakota, there's a greater variation in wind speed than in air density. The power in the wind varies with the third power of wind speed, but only the first power of density. When good wind sites are sought, wind speed is carefully considered, while density variations are usually neglected.

Wind Speed Variation Statewide

National wind assessments always rank North Dakota as one of the high wind states. Map 1 illustrates state winds and is drawn from material prepared by the "Pacific Northwest Laboratory," operated by Battelle for the United States Department of Energy under contract DE-AC06-76RLO 1830.

Map 1. North Dakota Annual Average Wind Power



The contours on this map give the average wind power at 32.8 ft. (10 m) and 164 ft. (50 m) above level ground with no nearby obstructions. A height of 10 m is used because it's a common international reference height for wind speed.

As will be seen later, it's important to specify the height at which data is given. Any area with an average wind-speed (at 10 m) greater than 12 mi/hr is considered very windy. Yet, there's a considerable varition in average wind-speed at points across the state.

While Map 1 is the best wind power map available at publication, it shouldn't be considered definitive.

First, there's doubt about the accuracy of the original wind-speed readings. Second, the anemometers which measured wind speed may not have been well maintained and may have been read inaccurately at times. And finally, the weather stations are often widely spaced, and wind speeds between them must be estimated.

In addition to the general variation in average wind-power in Map 1, there are other factors influencing average wind-power. The most important of these for wind-energy applications are terrain, height, time of year and time of day.

Wind Speed Variation With Height

The first 1,000 feet of the atmosphere is called the boundary layer. In this layer, ground friction affects the wind. The closer to the surface, the more significant the frictional forces slowing the wind.

All the data on average wind speed presented in Table 2 and Map 1 are at a height of 10 m above ground. Yet, since wind machines are usually installed above that height, it's necessary to estimate the wind speed at other elevations.

Over unobstructed level ground, the wind-speed variation with height is fairly well known. It can be assumed the wind speed over this type of surface varies with the one-seventh power of height.

Table 3 was derived from the one-seventh power law and allows height conversions to be made. To use the table, select the height in the left column which corresponds to the height at which your wind speed data was measured. Then, read across the top of the table to the height at which you expect to mount your wind machine. Finally, read down to find the conversion factor.

For example, if you decide you can put your WECS on a 50-foot tower and your wind speed data (say 13.0 mi/hr) was taken at 10 m height, you can then determine the average wind speed at 50 feet by reading across the 32.8 ft. (10 m) row to the "50 ft." column.

The correction factor is 1.06. Thus, the average wind-speed at 50-foot height is 13.0 mi/hr × 1.06 = 13.8 mi/hr. **Note:** In this example, you were planning to install your WECS on an unobstructed, level site. Data conversions for sites with obstructions on less-than-level ground are presented in Chapter Three.

Table 2. North Dakota Stations with Graphs of the Wind Characteristics

Station	Station[a] name	Lat (°N)	Long (°W)	Elevation of Station (m)	Elevation of Station ft	Period of Record (mo/yr)	Anem. Height (m)	Anem. Height ft	Annual Average Speed: Anem. Hgt. m/s	Anem. Hgt. mi/hr	At 10 m/s	At 10 mi/hr	At 50 m/s	At 50 mi/hr	Annual Average Power (watts/m²): At Anem. Height	At 10 m	At 50 m
Bismarck N. Dak.	Bismarck Airport	46.77	100.75	507	1663	1/48-10/61	13.1	43.0	4.9	11.0	4.8	10.7	6.4	14.3	161	154	370
Bismarck N. Dak.	Bismarck Airport	46.77	100.75	507	1663	10/61-12/78	6.1	20.0	4.4	9.8	4.7	10.5	5.9	13.2	122	150	301
Dickinson N. Dak.	Dickinson FAA	46.78	102.80	782	2566	12/48-7/64	9.1	29.9	6.1	13.6	6.2	13.9	7.8	17.4	250	259	518
Fargo N. Dak.	Hector Airport, Fargo	46.90	96.80	278	912	11/53-6/61	26.2	86.0	6.7	15.0	5.9	13.2	7.4	16.6	340	224	448
Fargo N. Dak.	Hector Airport, Fargo	46.90	96.80	278	912	6/61-12/78	6.1	20.0	5.3	11.9	5.6	12.5	7.1	15.9	165	203	407
Grand Fks. N. Dak.	Grand Fks. FAA	47.93	97.08	259	850	11/49-12/58	14.3	47.0	6.0	13.4	5.7	12.8	7.2	16.1	299	256	511
Grand Fks. N. Dak.	Grand Fks. AFB	47.97	97.40	276	906	5/60-11/68	4.6	15.1	4.6	10.3	5.1	11.4	6.4	14.3	139	194	387
Jamestown N. Dak.	Jamestown FAA	46.92	98.68	456	1496	12/48-12/54	8.8	28.9	5.4	12.1	5.5	12.3	6.9	15.4	228	238	475
Minot AFB	Minot AFB	48.42	101.33	504	1654	5/60-2/65	5.5	18.0	4.6	10.3	5.0	11.2	6.3	14.1	135	178	356
Minot AFB	Minot AFB	48.42	101.35	497	1630	4/65-11/68	5.2[b]	17.1	4.6	10.3	5.1	11.4	6.4	14.3	145	192	383
Minot N. Dak.	Minot Int. Airport	48.27	101.28	526	1726	12/48-9/58	6.4	21.0	5.5	12.3	5.8	13.0	7.4	16.6	194	234	468
Minot N. Dak.	Minot Int. Airport	48.27	101.28	526	1726	6/62-12/78	6.1	20.0	5.6	12.5	6.0	13.4	7.5	16.8	175	216	431
Pembina N. Dak.	Pembina CAA	48.95	97.25	242	794	12/48-6/50	13.7	44.9	6.0	13.4	5.8	13.0	7.2	16.1	279	243	486
Williston N. Dak.	Williston WBO[c]	48.15	103.62	581	1905	3/50-12/61	15.2	49.9	3.8	8.5	3.6	8.0	4.5	10.1	68	56	113
Williston N. Dak.	Williston Sloulin Int. Airport	48.18	103.63	581	1905	8/67-12/78	6.1	20.0	4.5	10.1	4.8	10.7	6.1	13.6	117	144	288

[a]FAA-Federal Aeronautics Administration Facility; AFB-Air Force Base; CAA-Civil Aeronautics Administration Facility; WBO-Weather Bureau Office.
[b]Anemometer height is approximate.
[c]Station had only 12 to 18 observations per day.
10m = 32.8 ft.
50m = 164 ft.

Wind Speed Variation With Season

Although wind power is almost the same for spring and winter throughout the state, winter wind power is slightly greater at locations in the northern part of the state, in the Canadian Wind Corridor. Spring has slightly greater wind power throughout the rest of the state, while summer is the season of lowest wind power throughout all of North Dakota.

During the winter, areas in the northeastern part of the state are subject to periodic southward surges of cold surface air from the northern Canadian plains. This phenomenon occurs frequently during the winter, when radiational heat loss from these plains causes a shallow high pressure system to develop, with a resulting strong surface pressure gradient.

During the winter, the state is subject to strong wind storms of relatively short duration. Such storms can occur when migratory low pressure systems originating on the lee side of the Rocky Mountains move through this region to the northeast.

The surface pressure gradient established is particularly strong when this occurs in conjunction with a surface high pressure system over the Canadian plains, as described previously. Two or three times each year this can create blizzards.

Consequently, much of the wind power in North Dakota is the result of high winds over short periods of time. One study shows that, during one January, nearly 85 percent of the total output of a 3-kW generator at Grand Forks occurred during a three-day blizzard (Krueger, 1976). Although this is an extreme example, this fact must be considered in any assessment of the state's wind resources.

Wind Speed Variation Daily

Wind speeds vary considerably during the day, and for some applications, it may be important to know these daily, or diurnal, variations.

Maximum wind values occur in the afternoon, around 2 p.m. Central Standard Time (CST), while minimum values occur during the early morning, around 5-6 a.m.

The physical explanation behind the maximum and minimum wind speeds is that the surface air becomes heated during daylight hours and rises to mix with the faster upper-level winds. The surface air is warmest during mid-afternoon and, because of the large vertical energy transfer from the upper layer to the lower layer, the highest wind speeds occur at this time.

During the evening hours there's no solar heating, so the surface wind speed decreases, with a minimum occurring during the coolest hours of early morning. As the sun "rises," heating begins and the cycle repeats.

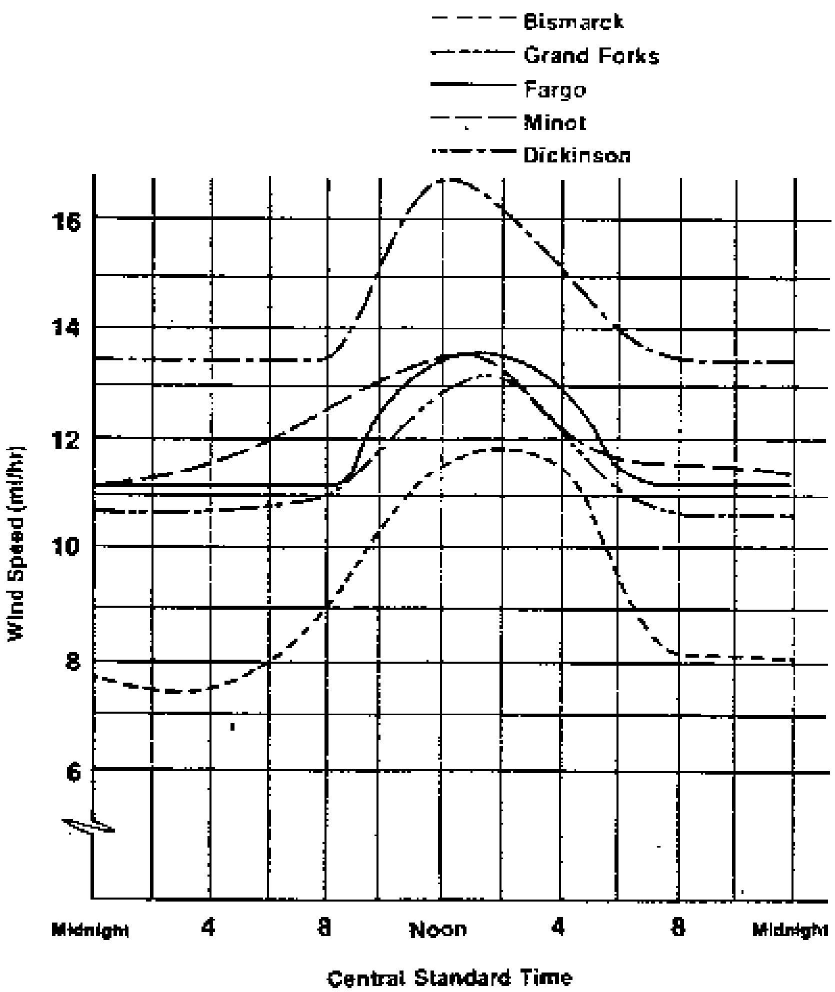
Wind Speed Variation From Year to Year

Wind-speed also varies

Table 3. Wind Conversion Factors for Height (in feet)

	Height at which wind speed is to be found										
Height at which wind speed is known	20	25	30	32.8 (10 m)	35	40	45	50	60	75	100
20	1.0	1.03	1.06	1.07	1.08	1.10	1.12	1.14	1.17	1.21	1.26
25	.97	1.0	1.03	1.04	1.05	1.07	1.09	1.10	1.13	1.17	1.22
30	.94	.97	1.0	1.01	1.02	1.04	1.06	1.08	1.10	1.14	1.19
(10 m) 32.8	.93	.96	.99	1.0	1.01	1.03	1.05	1.06	1.09	1.13	1.17
35	.92	.95	.98	.99	1.0	1.02	1.04	1.05	1.08	1.12	1.16
40	.91	.94	.96	.97	.98	1.0	1.02	1.03	1.06	1.09	1.14
45	.89	.92	.94	.96	.96	.98	1.0	1.02	1.04	1.08	1.12
50	.88	.91	.93	.94	.95	.97	.99	1.02	1.03	1.06	1.10

Figure 15. Daily Average Wind Speeds (winter)



from year to year; that is, there are windy years and calm years.

There's apparently no pattern to the variation; the changes occur in a random manner. The result is that, even though the site's average wind-speed is known, its average wind-speed during any particular year will probably differ from this long-term average by up to 10 percent.

A second consequence of this variation is that a large number of years of data is needed before the actual long-term average can be estimated. These two factors make average wind-speed calculations difficult.

Wind Speed Velocity Frequency Curve

Thus far in this chapter, information has centered on the "average wind-speed." The spring months show higher average wind

Table 4. Monthly Average Wind Speed (in miles per hour at 10 meters)

Years for Average	1/61-12/78	12/48-7/64	6/61-12/78	5/60-11/68	12/48-12/54	6/62-12/78	12/48-9/50	8/67-12/78
Month	Bismarck	Dickinson	Fargo	Grand Forks	Jamestown	Minot	Pembina	Williston
January	10.1	14.5	13.0	12.8	13.0	14.8	15.2	10.7
February	10.7	14.5	12.8	12.9	13.0	14.3	13.8	11.2
March	11.2	15.2	13.4	12.8	14.1	14.1	13.0	11.4
April	12.6	15.4	13.9	13.3	14.3	14.3	15.6	12.5
May	12.1	14.5	12.8	13.3	12.9	13.9	13.4	12.1
June	10.3	13.4	11.9	10.1	12.5	12.8	12.5	11.2
July	9.8	12.3	11.0	9.1	10.2	12.1	10.3	10.3
August	9.8	12.6	11.9	9.6	10.2	12.4	10.3	10.2
September	10.3	13.4	12.3	10.5	12.0	13.0	12.1	10.7
October	10.5	13.9	13.0	11.5	13.0	13.4	15.2	11.4
November	9.8	15.2	12.8	11.4	12.5	13.0	13.4	10.3
December	10.3	14.3	12.3	12.5	11.4	13.8	12.1	10.3

speeds than other months, and wind speeds are typically higher in the afternoon than at any other time of the day.

Obviously, wind speed can differ greatly from the average at any particular time. Strong cold fronts can produce 40 mi/hr north winds at any time of day. Thunderstorms produce strong winds in the summer, while some spring afternoons are completely calm.

Thus, more than a table of average wind speeds is needed to describe the wind. A velocity frequency (Table 3) is used to show how wind speed varies.

Wind Direction

Knowledge of the wind's prevailing direction can be important when deciding where to install a wind machine. A wind "rose" tells the direction which the wind tends to blow.

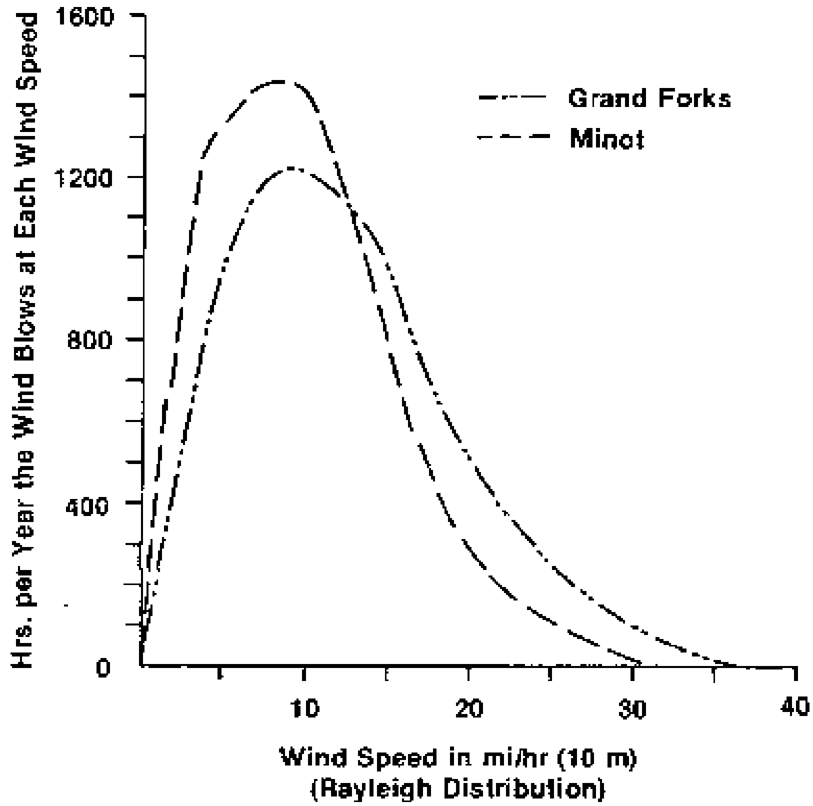
Figure 18 presents wind roses for four sites in North Dakota. The spikes on each rose represent the percentage of wind from that direction (i.e. the longer the spike, the higher the percentage of wind from that direction).

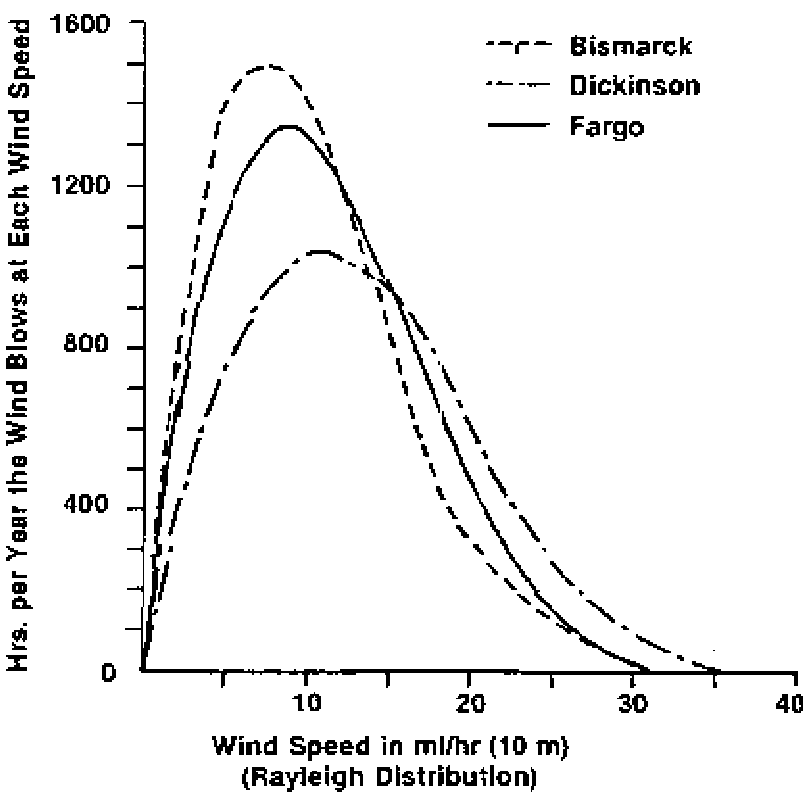
Turbulence

The final wind characteristic to be considered is turbulence (rapid changes in wind speed and direction).

Because of ground friction forces and surface ob-

Figures 16 & 17. Annual Wind Speed Duration Curves (Rayleigh Distribution)





structions, turbulence is more severe near the ground. It's hard on wind machines; the stresses from abrupt direction changes strain the entire structure.

For this reason, WECS generally shouldn't be mounted at less than 30 feet in height, even on an unobstructed level site. If large obstructions are present, the machine should be well above them.

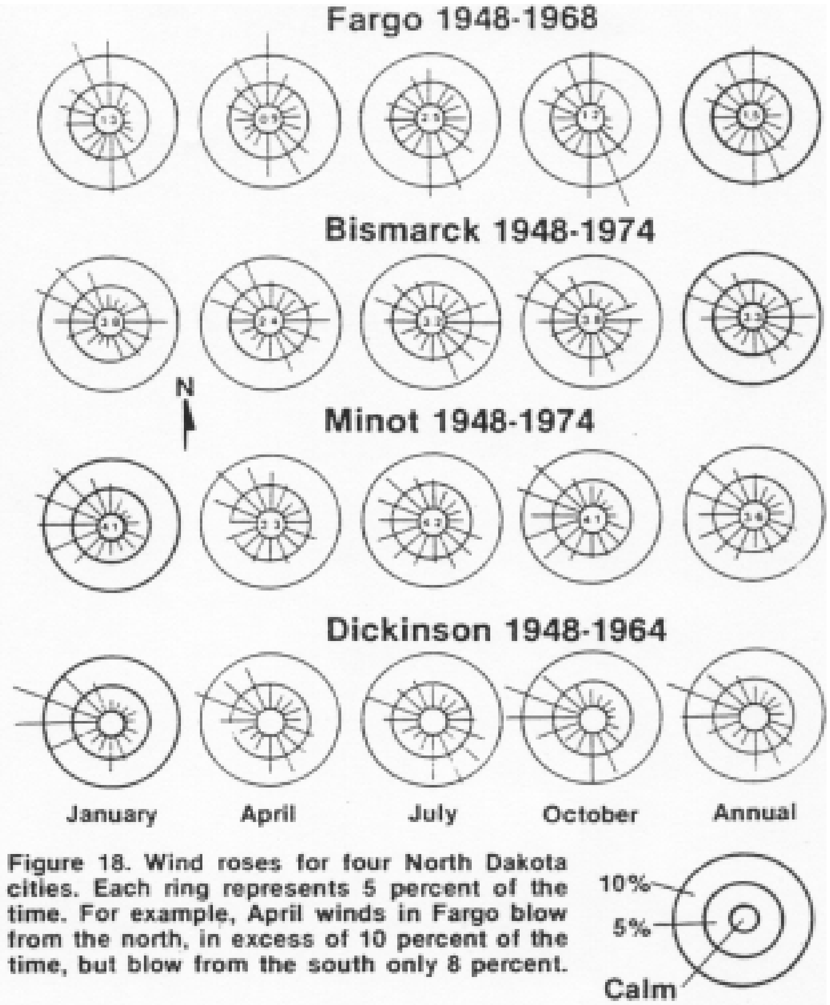
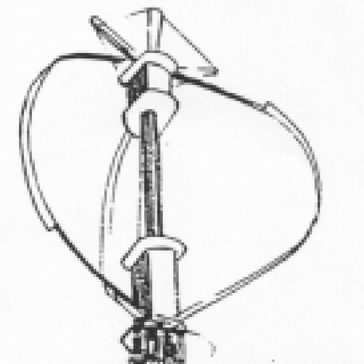


Figure 18. Wind roses for four North Dakota cities. Each ring represents 5 percent of the time. For example, April winds in Fargo blow from the north, in excess of 10 percent of the time, but blow from the south only 8 percent.



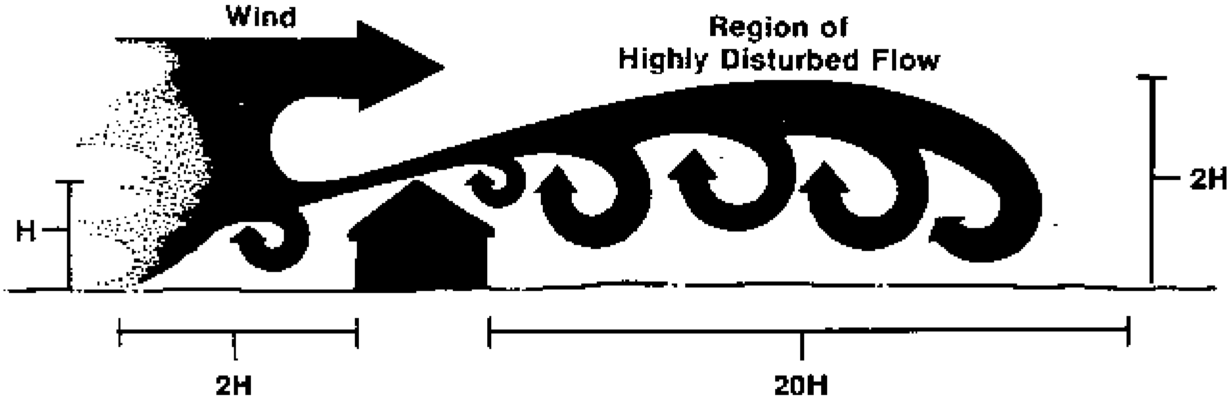
Chapter Three: Evaluating WECS Sites

If North Dakota was a treeless plain, then Map 1 could be used, without correction, to determine average wind speed for any WECS site.

However, many potential sites aren't level and/or unobstructed; they have features nearby altering the wind patterns. These surrounding features must be examined for their effect on wind speed.

It should be no surprise the wind is affected by the type terrain over which it flows. A hill or other obstruction will impede the wind, while a rough surface will produce more

Figure 19. Potential Wind Turbulence Areas Around Buildings.



friction near the ground than a smooth one.

For this reason, site evaluation can be quite complicated near some landforms. Since North Dakota terrain isn't as complex as that found in some parts of the country, this discussion will consider only simpler terrain.

Site evaluations can be difficult. Map 2 divides North Dakota into zones characterized by different slopes and local relief.

The state's terrain varies from eastern flat plains to the southwestern hilly plains and tablelands.

The highest relief is found in the Badlands of the Little Missouri River and on the Missouri Plateau in western North Dakota. The elevation generally increases gradually from east to west, with steeper rises along the Pembina and Missouri Escarpments (Map 2).

The general area bounded approximately on the west by the Missouri Coteau and with a less well-defined boundary east of the Red River appears to be significant in channeling the dense arctic air that periodically pours southward from Canada toward Iowa during the winter.

Eastern North Dakota's Red River Valley is bounded on the west by the Pembina Escarpment and has a south-to-north decrease in elevation, with the Red River flowing north to Hudson Bay.

Obstructions

Site evaluation techniques over the smooth and irregular plains (Map 2) are fairly well defined. Obstructions and surface roughness are the only variables affecting the wind flow.

On flat land the effect of such obstructions as buildings and trees is to (1) slow the wind and (2) produce turbulence. Lower wind-speeds mean the WECS will produce less energy. In addition, turbulence will stress the machine anc probably shorten its life.

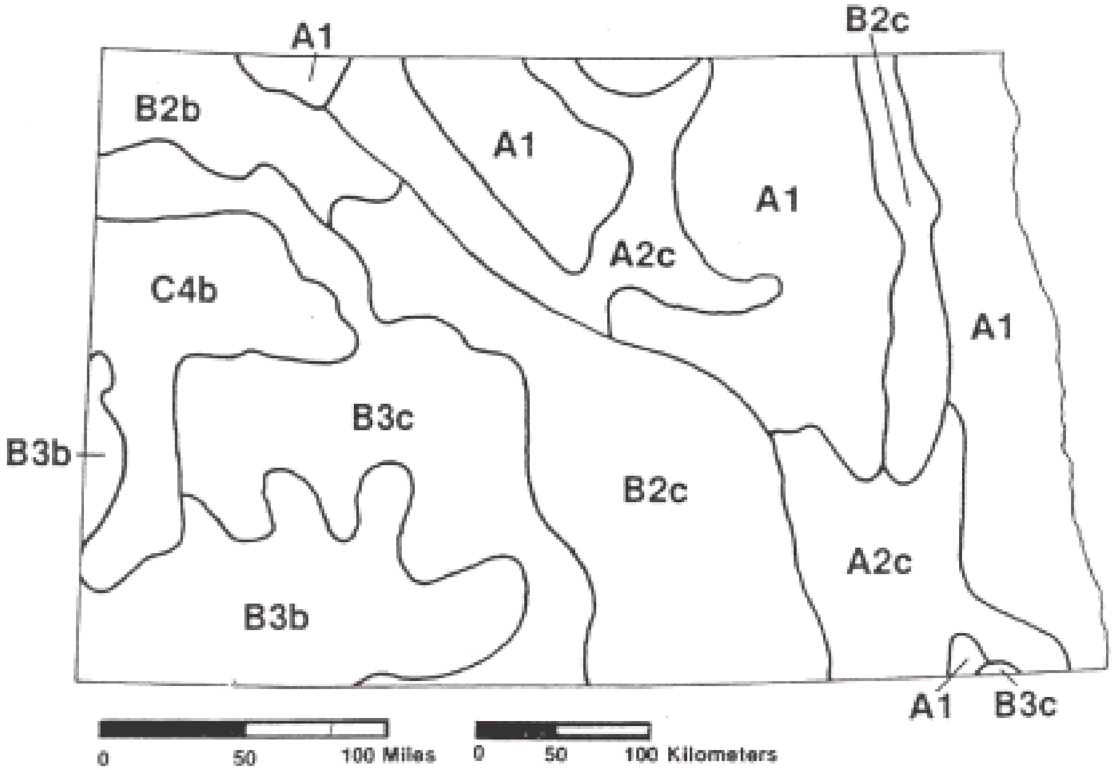
The general rule is very clear — stay as far away from obstructions as possible.

Unfortunately, this rule gives little concrete guidance. How far away is enough? Consider Figure 10. If a building has a height, "H," then the shaded area indicates the region of highly disturbed wind-flow, given the indicated direction of the wind.

The highly disturbed region can extend upward twice the building's height, downwind 20 times the building's height and upwind twice the building's height.

While it's a good idea to locate a wind machine out of the turbulent region, it's not always possible. Table 5 can be used to aid in locating wind sites; it shows the wind speed decrease and turbulence increase downwind of the building.

Map 2. Map of Land Surface Forms of North Dakota



LAND-SURFACE FORM LEGEND

PLAINS
A1 . . . . FLAT PLAINS
A2 . . . . SMOOTH PLAINS
B2 . . . . IRREGULAR PLAINS

PLAINS WITH HILLS OR MOUNTAINS
A.B3a.b PLAINS WITH HILLS

OPEN HILLS AND MOUNTAINS
C2 . . . . OPEN LOW HILLS
C4 . . . . OPEN HIGH HILLS

TABLELANDS
B3c.d . . . . TABLELANDS, MODERATE RELIEF

SCHEME OF CLASSIFICATION
SLOPE (1st LETTER)
A . . . . 80% OF AREA GENTLY SLOPING
B . . . . 50-80% OF AREA GENTLY SLOPING
C . . . . 20-50% OF AREA GENTLY SLOPING

LOCAL RELIEF (2nd LETTER)
1 . . . . 0 TO 30m (1 TO 100 ft)
2 . . . . 30 TO 90m (100 to 300 ft)
3 . . . . 90 TO 150 m (300 to 500 ft)
4 . . . . 150 TO 300m (500 to 1000 ft)

PROFILE TYPE (3rd LETTER)
b . . . . 50-75% OF GENTLE SLOPE IS IN LOWLAND
c . . . . 50-75% OF GENTLE SLOPE IS ON UPLAND

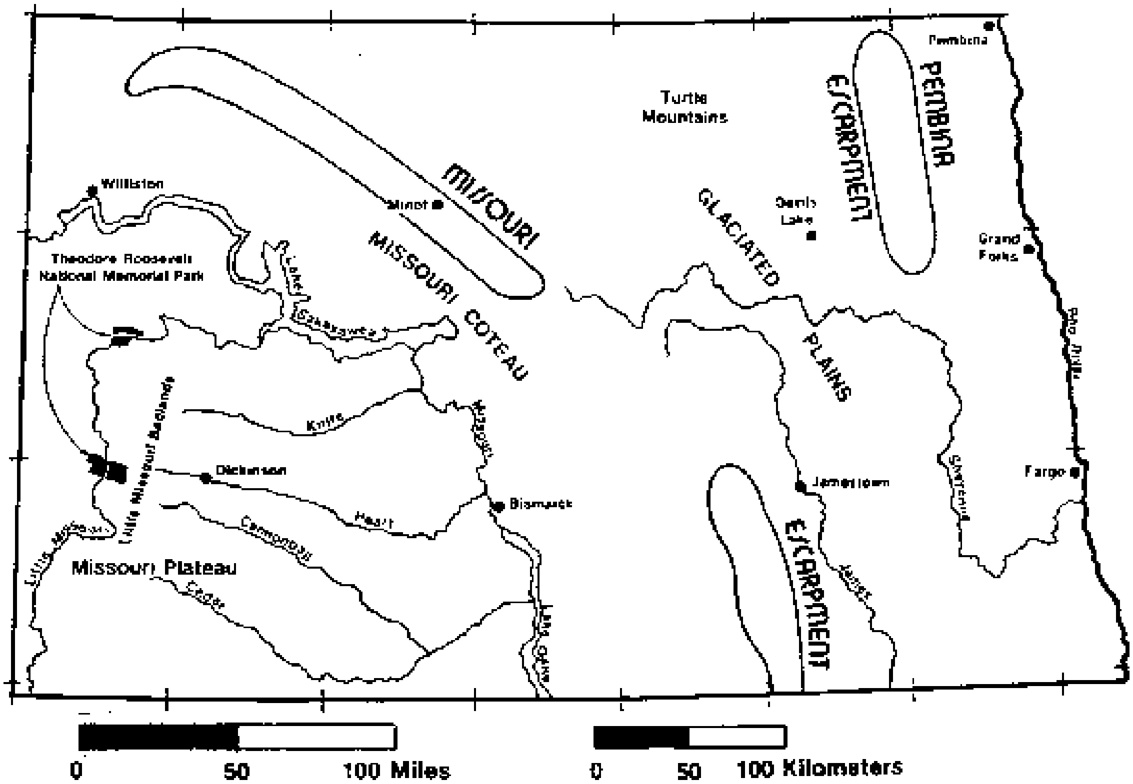
From wind rose information in Chapter Two, it's evident a site located east or west of a building is better than a site located north or south, given the predominate north-south axis of the state's winds.

If a building obstruction can't be avoided, place the WECS downwind of the least-common wind direction to get the minimum impact or consider mounting it at least twice the height of the obstruction.

Table 5 also generalizes speed decrease and turbulence increase for such common obstructions as shelterbelts and individual trees. As it happens, the effect of shelterbelts on the winds is similar to, but even more pronounced than, the effect of buildings.

Wind can still be significantly affected as much as 20 times the shelterbelt height downwind from a shelterbelt. (Table No. 5 is for wind speeds at about

Map 3. Geographic Map of North Dakota



the same height above ground as the shelterbelt.) Notice a shelterbelt with some porosity affects the wind more than a very dense one.

For example, at a distance 10 times the height downwind of a 20-percent porosity shelterbelt, the wind is only 60 percent of its original velocity. With a 0-percent porosity (a solid barrier), the wind speed 10 H downwind is 85 percent of the unobstructed value.

At 5 H downwind, both the 20-percent and 40-percent porosity shelterbelts affect wind speed tremendously, and markedly increase turbulence. The affect of an isolated tree is like that of a building, but often more severe since the tree is porous.

To summarize: stay out of the influence of the most prominent downwind obstruction zones if possible. If you must locate downwind from an obstruction, try to have the WECS at a height two or three times the obstruction's height, or use Table 5 to estimate how much wind speed is reduced.

To make this estimation, take the percentage of time the site is downwind from a given direction (use the wind rose in Figure 18 nearest your site if local information isn't available) and reduce the wind speed by the percent given in Table 5. Add all these adjusted directional wind-speeds to find the new total wind-speed corrected for obstructions.

The site should usually be located upwind of the obstacle a distance of at least twice the obstruction's height. It's not easy to determine how far to the side of an obstruction a WECS should be placed.

If the obstruction is more than 10 feet wide, the WECS probably should be placed at least twice the obstruction's width to the side. Some guidance on needed side clearance is indicated as "width of turbulence" in the tree section (Table 5).

Table 5. Effect of Building Shape on Wind Speed and Turbulence Downwind Distances (In Terms of Building Heights)

Building Shape (Width/Height)	5H			10H			20H		
	Percent Speed Decrease	Percent Power Decrease	Percent Turbulence Increase	Percent Speed Decrease	Percent Power Decrease	Percent Turbulence Increase	Percent Speed Decrease	Percent Power Decrease	Percent Turbulence Increase
4	36	74	25	14	36	7	5	14	1
3	24	56	15	11	29	5	4	12	0.5
1	11	29	4	5	14	1	2	6	-
0.33	2.5	7.3	2.5	1.3	4	0.75	-	-	-
0.25	2	6	2.5	1	3	0.50	-	-	-
Height of the Disturbed Flow Region.	1.5H			2.0H			3.0H		

Power Loss and Turbulence Increase Downwind From Shelterbelts

Porosity (Open Area, Total Area)	5H			10H			20H		
	Percent Speed Decrease	Percent Power Decrease	Percent Turbulence Increase	Percent Speed Decrease	Percent Power Decrease	Percent Turbulence Increase	Percent Speed Decrease	Percent Power Decrease	Percent Turbulence Increase
0% (no space between trees)	40	78	16	15	39	18	3	9	15
20% (with loose foliage such as pine or broadleaf trees)	60	93	9	40	78	-	12	32	-
40% (with dense foliage such as Colorado Spruce)	70	97	34	55	90	-	20	49	-
Top of Turbulent Zone	2.5H			3.0H			3.5H		

Speed and Power Loss Downwind From Single Trees

Distance Downwind (in Tree Widths)		5	10	15	20	30
Dense-foliage tree (such as Colorado spruce)	Maximum percent loss of velocity	20	9	6	4	3
	Maximum percent loss of power	49	25	17	13	9
Thin-foliage tree (such as a pine)	Maximum percent loss of velocity	16	7	4	3	2
	Maximum percent loss of power	41	18	12	8	6
Height of the turbulent flow region (in tree heights)		1.5	2.0	2.5	3.0	3.5
Width of turbulent flow region (in tree widths)		1.5	2.0	2.5	3.0	3.5

In addition to wind speed reduction, Table 5 lists turbulence effects. The amount of turbulence — a sudden change in wind speed and direction — is proportional to the wind speed and the roughness shape of the terrain over which the wind passes.

Turbulence creates stress on the WECS which usually shortens its life. Experience has shown WECS located close to turbulence-creating obstructions may last only a year or two before some type of mechanical failure occurs.

Therefore, consider turbulence as well as wind speed when selecting a WECS site. The selected site probably shouldn't increase the turbulence more than a few percent above that occurring at ground level. Table 5 gives some guidance on the distance the WECS should be from obstructions to keep the turbulence low.

When considering turbulence, don't overlook the obvious. In addition to trees and buildings, terrain such as steep cliffs and rolling hills can also cause turbulence.

Turbulence at a particular site can be estimated with a kite. Tie several pieces of 4- to 6-foot-long ribbon to the kite string and fly the kite.

Turbulence will cause the kite and its ribbons to fly erratically and flop around excessively. If the kite flies smoothly and its ribbons swirl around, it's above the turbulence zone. If it flies smoothly and its ribbons fly straight in the wind, turbulence probably won't be a problem.

Since turbulence varies with wind speed, weather conditions and height, there are several guidelines that must be followed when using this procedure.

Fly the kite at or near the machine's hub height. In addition, it should be flown when the maximum turbulence normally occurs — a sunny and moderately windy day. The preferred wind speed for flying the kite is around 15-20 mi/hr, a moderate but common wind-speed.

Another method of observing turbulence involves using a large helium filled balloon, with 4-foot streamers attached to a streamer line and an auxiliary tether line to hold the balloon in position (see Figure 20).

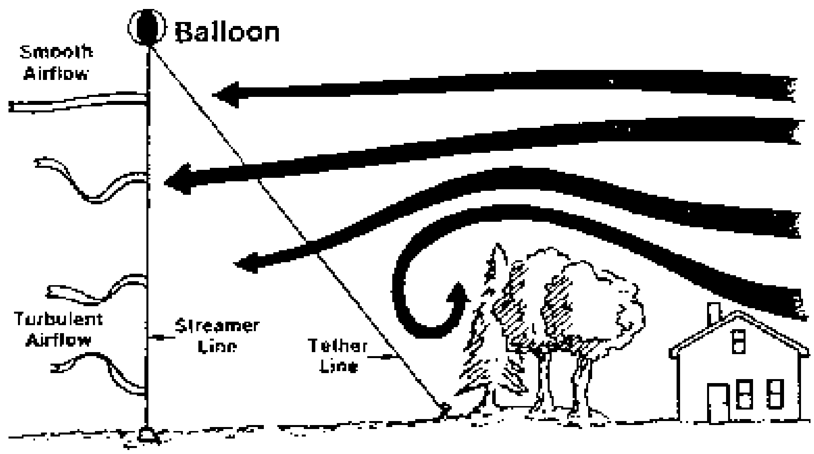


Figure 20. A simple method for detecting turbulence. Streamers attached to a pole, kite or balloon at 4-foot intervals will indicate how high you'll have to go with your tower to rise above turbulence caused by obstacles.

When the above steps are followed, a reasonable estimation of site turbulence can be made.

Surface Roughness

Friction from ground resistance to wind flow is the primary reason wind speed increases with height.

However, the rate increase varies with the surface type. Each surface has a different roughness and this in turn creates a different speed-versus-height relationship.

Figure 21 illustrates wind velocity profiles over water and tall grass. Notice how quickly the over-water wind-speed increases with height, compared to that over tall grass.

In fact, given equivalent weather conditions, winds at 10 m over water are twice as great as winds at 10 m over tall grass. The water surface is usually smooth and impedes the wind less than the greater surface roughness of the grass.

The annual average wind power density in North Dakota is shown in Map 1. (Average wind speed is given in the accompanying table). This analysis of mean wind power applies to terrain features favorably exposed to the wind.

However, nearby terrain features may interact with the wind field to cause the wind power at some exposed sites to vary as much as ± 50-100 percent from the values shown in the figure. From that assessment value, sites with other surface type need to be adjusted.

Table 6 can be used to adjust average wind-speed with surface roughness. The information needed to use this table includes the area's average wind-speed at 10 m height (from Map 1 or other source), the type of surface at the site (average surface feature within a mile of the site) and the anticipated WECS mounting height.

For example, if you plan to install a WECS on a 60 ft. tower, over an area covered with scrub trees and brush, with site wind-speed (from Map 1, wind speed given at 10 m) in a 13.4 mi/hr zone, you'll find the surface factor for a height of 60 feet with "tall row crops or low woods" is 1.16.

The corrected wind speed is the 10 m wind speed times the surface factor or 13.4 mi/hr × 1.16 = 15.54 mph.

The surface cover to be used with Table 6 is that around the site for about a mile. Sometimes, there are different surfaces around a site, and a composite surface must be estimated. The roughness upwind of the site is most important.

For example, if a site is on the north edge of a lake about a mile across, the surface used to evaluate wind speed for south winds would be a water surface, since the wind wouldn't have had a chance to change its characteristics before being intercepted by the wind machine.

Since the surface to the north of the WECS would be different, the overall average wind-speed could be calculated using the directional percentage of wind in the same manner as correcting for obstructions. Multiply the wind's directional percentage by the average wind-speed by the appropriate directional surface factor. Adding these figures will produce the annual wind-speed corrected for surface roughness.

The Effects of Hills and Valleys

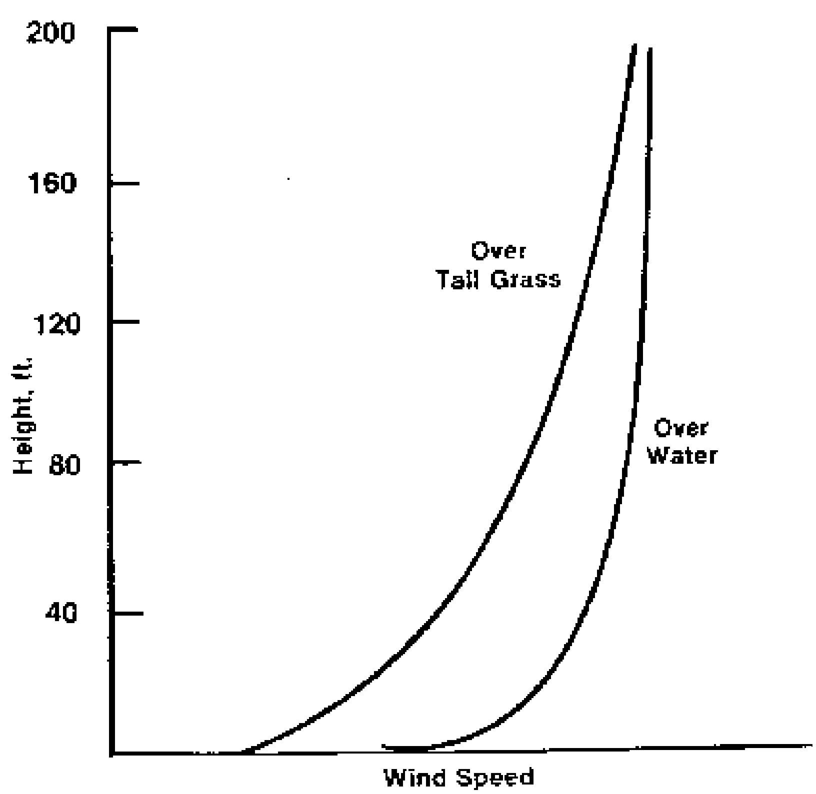
Siting in complex terrain can be very complicated. The average wind-speed, even on a hill top, can be affected by several factors, with the result it might not be possible to accurately estimate wind-speed without a long-term measurement procedure. If your site is like any of the following examples, try these correction techniques:

If your site is an isolated hill with a gradual slope, its natural elevation can, under certain circumstances, increase tower height and place the WECS in the higher wind zone.

For this to happen, the hill has to have enough slope to allow the upper-level winds to pass undisturbed over the tops of any surrounding hills (Figure 22)

If the slope (height/length) is greater than 1:20, i.e. a 5 percent slope, the hill's height doesn't really

Figure 21. Wind Speed Over Tall Grass vs Water



matter. When these conditions are met, a simple addition of the hill and tower heights will give a new effective wind height with which to estimate the WECS wind speed.

Ground slope can be estimated from United States Department of the Interior Geological Survey Quadrangle maps, available from the State Water Commission, Bismarck.

If your site is on a gentler hill (Fig. 23), with a slope of less than 1:20, or on a series of rolling hills, you can rarely increase the wind speed, since the ground level for measuring wind speed is already considered to be the peaks of the hills.

Since additional turbulence may also occur near rolling hills, turbulence measurement is recommended if your site is situated in such a location.

A WECS' wind speed can be increased by placing it higher in the wind stream, or by siting it on certain landforms, such as hills or ridges, over which wind speed is enhanced by the aerodynamics of the land itself.

As a classic example, consider a long ridge, running east-west, as shown in Figure 24.

In such a case, the wind speed directly above the ridge crest will be greater than the wind upstream of the site by a factor $1+S=2\times H/L$ (H is the ridge's height and L its horizontal width from the center).

For this effect to occur, the minimum hill height is about 75 feet, and the hill or ridge's slope (H/L) should be 1:20-1:3.5, i.e. 5-29 percent slopes.

In addition, the ridge's side should be smooth,

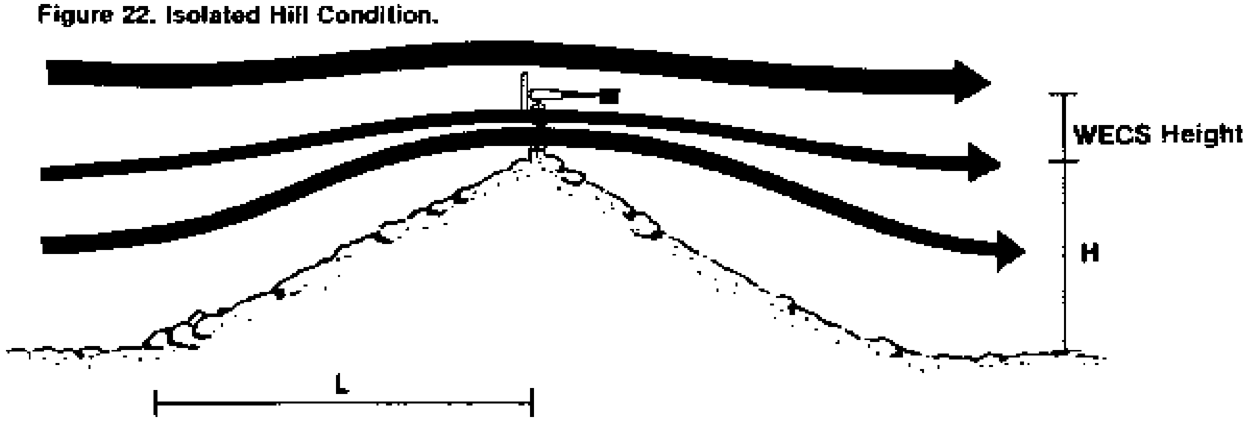
Table 6. Extrapolation of the Wind Speed from 30 ft to Other Heights over Flat Terrain of Uniform Roughness [a]

Roughness Characteristic	20	40	60	80	100	120	140	160[b]	180[b]	200[b]
Smooth surface ocean, sand	0.94	1.04	1.10	1.15	1.18	1.21	1.24	1.26	1.19	1.30
Low grass or fallow ground	0.94	1.05	1.12	1.17	1.21	1.25	1.28	1.31	1.33	1.35
High grass or low row crops	0.93	1.05	1.13	1.19	1.24	1.28	1.32	1.35	1.38	1.41
Tall row crops or low woods	0.92	1.06	1.18	1.23	1.29	1.34	1.38	1.42	1.46	1.49
High woods with many trees	0.89	1.08	1.21	1.32	1.40	1.47	1.54	1.60	1.65	1.70
Suburbs, small towns	0.82	1.15	1.38	1.60	1.78	1.95	2.09	2.23	2.36	2.49

[a]The table was developed using power law indices obtained from C. Huang, Pacific Northwest Laboratory, Richland, WA 99352.

[b]These three columns should be used with caution because extrapolation to levels more than 100 ft above or below the base height may not be completely reliable.

Figure 22. Isolated Hill Condition.



Effective WECS height = WECS height + H when H:L = 1:20 or greater

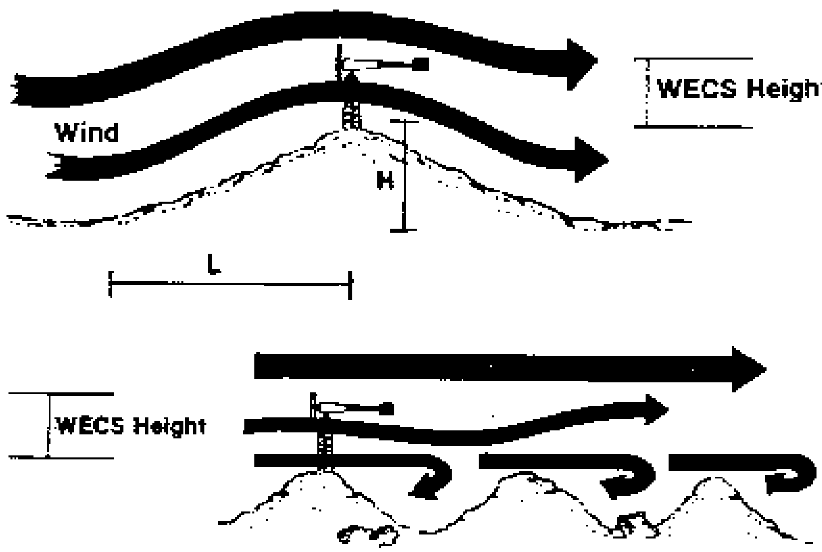
and the terrain for 1-2 miles upwind should be smooth and with no obstructions.

When such ridges are identified, they can become the sites of very desirable WECS.

While sites atop hills are desirable, siting in river valleys or areas surrounded by ridges or hills should be recognized as potential problem areas.

Periods of calm and light winds often occur in valleys during the evening and early morning hours. In deep valleys, winds have a tendency to flow overhead, reducing the winds on the valley floor.

Figure 23. Gradual Isolated Hill and Rolling Hill Conditions.



Effective WECS height = WECS height when H:L = less than 1:20 and/or in rolling hills

Direct Measurement of Average Wind-Speed

If there's an unusual terrain feature near the site, or if the features are very complex, making it difficult to use the rules presented here, a direct wind speed measurement can be made with an anemometer.

The best measurement is obtained by installing the anemometer at the location and height being considered for the WECS. However, since it's expensive to put up such a tall tower just to house an anemometer, it may be better to mount the instrument about 10 m high.

You can buy an anemometer with a simple run-of-the-wind readout for about $200. The output reading is simply the miles of wind which have passed the instrument since the last reading.

For example, if the readout is checked weekly, the average wind-speed for a week with a reading of 2,200 miles is the reading (in miles) divided by the number of days times 24 hours, or $2{,}200/(7 \times 24) = 13.1$ mi/hr.

An anemometer can be mounted on any available tower. A 30-foot tower can be purchased for about $30. A simple adapter will probably have to be made to mount the instrument on the tower. Polypropylene rope (or any other non-stretching rope or wire) and metal stakes can be used to hold the tower up, and it can be set on a steel or wood baseplate to keep it from sinking into the ground.

By the time all the necessary equipment is purchased, the simplest anemometer system will probably cost about $300. Anemometers which can automatically calculate and record average wind-speed may also be used, but their purchase will increase the over-all price. Very sophisticated systems, costing thousands of dollars, are also available, but the simple system is adequate for most small WECS users.

To obtain an accurate indication of average wind-speed, anemometer measurements must be taken for a considerable time. About one year is needed to be reasonably certain of being within 10 percent of the actual wind speed. Each additional year will reduce the error by 1 percent.

For example, if the wind was measured for three years, you can be reasonably confident of being within 8 percent of the "actual" average wind-speed. Since the wind varies seasonally, the measurement should be done in yearly multiples, or a correction made to the measured wind speed according to what season the measurement was made.

Correlation measurements to determine average wind-speed using only a short measurement period have been suggested. Using this method, anemometer measurements over a short period of time are compared to measurements at a nearby weather station for the same period of time.

The difference between these short-term measurements is then assumed to also represent the difference between the actual average wind-speeds at the two locations. Since the long-term average at the weather station is known, the site's average wind-speed can be estimated.

Although this method looks good on paper, it has not worked well in controlled experiments, and its use is suspect. If it's used, the site probably shouldn't be over 10-20 miles from the weather station, and the two terrains should be similar.

For large WECS systems, say at least 100 kW or larger, a site measurement program can be justified.

However, due to the expense and time needed to properly measure wind speed, most prospective small WECS owners don't utilize an on-site anemometer system.

But, if a unique site demanded such, a useful short-term site anemometer installation might be to use two recorders — one instrument on the site and the other on unobstructed level ground not too far away — and compare the two readings.

In a few weeks, such site specifics as the speed-up on a hilltop, or the shielding effect of an obstruction, could be determined.

Other Information

Since the rules given here are simple, any site will probably have some subtleties which will cause deviations.

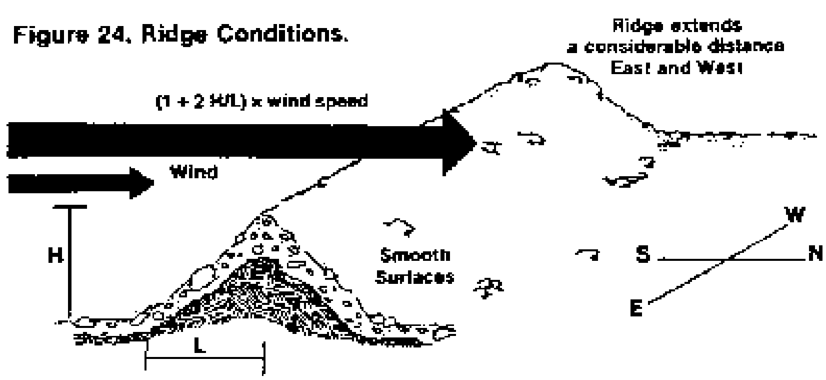
Some of the information in this chapter was taken from an excellent book, "A Siting Handbook for Small Wind Conversion Systems," by Battelle Memorial Institute. Check with your local library or university for a copy, or see Appendix A for information on how to obtain your own.

WORKSHEET 1

Complete Worksheet 1 to Line 6; this will give you the estimated annual wind-speed for your site or sites. Use Table 2 or best available information to complete Line 1. Use Table 3 for Line 2. Use Table 5 for Line 3, Table 6 for Line 4 and Figures 22, 23, and 24 for Line 5.

Worksheet 1, lines 7-14 are addressed in Chapters four and five. The figures for Line 11 can be recorded from your utility bill. Worksheet 2 will be utilized before you complete Worksheet 1.

Figure 24. Ridge Conditions.



Worksheet 1
North Dakota Wind Energy Handbook

	Site 1	Site 2	Site 3
1. Average wind-speed at ________ height	________	________	________
2. Wind-speed corrected for height	________	________	________
3. Wind-speed corrected for obstructions	________	________	________
4. Wind-speed corrected for surface	________	________	________
5. Wind-speed corrected for hills	________	________	________
6. Estimated annual wind-speed	________	________	________

	WECS 1	WECS 2	WECS 3
7. Annual electrical production	________	________	________
8. Utilization factor	(________)	(________)	(________)

	WECS 1 used	WECS 1 return	WECS 2 used	WECS 2 return	WECS 3 used	WECS 3 return
9. Annual energy:used and returned	____	____	____	____	____	____
10. Monthly energy:used and returned	____	____	____	____	____	____

Present electrical use:	kWh	$
January	________	________
February	________	________
March	________	________
April	________	________
May	________	________
June	________	________
July	________	________
August	________	________
September	________	________
October	________	________
November	________	________
December	________	________

Decrease lines 11 and 12 if you expect to institute conservation measures; increase them if you expect to add electrical consumption with new uses or machines (color TV, etc.).

	kWh	$	
11. Present annual electrical use	________	________	(year________)
12. Monthly average electrical use	________	________	
13. Electrical rate(s)	________		base or service charge
	________		
	________		

	WECS 1	WECS 2	WECS 3
14. Estimated monthly savings	________	________	________

Chapter Four: Energy Output

After the site's average wind-speed has been estimated, or its complete wind characteristics obtained, a WECS energy output can be calculated.

The energy output determines how well a particular WECS will match an application, and dictates to a large extent the wind generator's economic value.

A wind machine's output is usually stated in terms of kilowatt hours (kWh) per year or month. Two of several methods of estimating this output will be presented here. Given the monthly or yearly energy estimates, the WECS' worth can be determined.

Energy Output Using Velocity Frequency Data

The first method of estimating a WECS' energy output requires a graph displaying the output as a function of wind speed, a curve which is generally supplied by the manufacturer.

A hypothetical curve is shown in Figure 25. This curve is for a 4-kW machine which reaches rated power at about 24 mi/hr.

The machine begins to generate power at around 10 mi/hr. Between 24-36 mi/hr, some type of power limiting is used to give a more-or-less constant output, and for wind speeds above 36 mi/hr, the machine shuts down.

This illustrated curve isn't for any particular wind machine, although its shape is similar to those of a number of machines presently on the market.

The WECS power output at each wind speed is given by this curve. For example, if the wind is blowing at 20 mi/hr, the curve indicates the output should be about 2.5 kW.

If it's known how many hours each year the wind blows at each speed, the WECS' expected yearly energy output can be estimated. As shown in Chapter two, the number of hours the wind blows at each wind speed is given by the velocity frequency curve. Combining data from the site's velocity frequency curve with a specific machine's output curve gives a first approximation of the annual energy output.

Table 7 continues Figure 25's hypothetical example of a WECS installed at a height of 60 feet on an unobstructed level site near Fargo.

Looking at the wind characteristics for Fargo in Table 7 (data corrected to 60 feet), you can see a 20 mi/hr wind blows, on the average, for about 710 hours each year. The 20 mi/hr winds will generate 2.5×710, or 1,775 kWh of energy each year.

If all the different wind speeds are considered, the total yearly energy output can be estimated — in this case, 9,155 kWh as a likely maximum output.

On the average, this 4-kWh machine would generate about 763 kWh per month (9155 ÷ 12). The actual output, of course, would vary from month to month, with the spring months expected to have the highest output and the summer months the lowest.

Estimating Power Output from Annual Average Wind Speeds and WECS Characteristics

The amount of power a WECS will produce

depends on its operating characteristics and the wind's frequency distribution.

In the following analysis, the hourly wind speeds are assumed to have a Rayleigh frequency distribution. Using the Rayleigh distribution analysis for North Dakota winds, a generic wind turbine output power versus wind speed graph, appropriate curves can be generated.

These curves can be used to calculate the wind turbine's average annual power output, knowing the average annual wind speed, the cut-in rated and cut-out speed of the wind turbine.

Figure 26 is' the curve used with this method to calculate the annual average power output.

The following example, using the wind and wind turbine characteristics of the example on page 33, shows how this calculation is made.

Location is Fargo, North Dakota. Annual average wind speed is 12.5 mph @ 10 m.

Hypothetical wind machine characteristics.

	4 kWh
Cut-in speed	10 mph
Rated wind speed	24 mph
Cut-out speed	36 mph

CI (Cut-in speed) = Wind speed below which the generator produces no electricity.

RS (Rated speed) = The lowest speed at which the generator produces power at its rated capacity.

CO (Cut-out speed) = The speed above which the generator doesn't operate (due to hazardous winds).

AA (Annual Average Wind Speed.)

1. Calculate the following ratios:

$$\frac{CO}{RS} = \frac{36}{24} = 1.50$$

$$\frac{AA}{RS} = \frac{13.6}{24} = 0.57$$

AA = 12.5 mi/hr@10 m

From Table 3, the wind correction factor is 1.09, using speed measured at 10 m.

Height at which wind speed is to be found = 60 ft.

AA = 12.5 × 1.09 = 13.6 mph

From Figure 26

$$\frac{\text{Average Power Output}}{\text{Rated Power}} = .290$$

Annual average power output = .290 × 24 × 365 × 4 = 10,161 kwh

Annual average power output = 10,161 × .75 = 7621 (Using the 75% operating factor)

Table 9 can also be used to calculate the annual average power output from the average wind speed.

The use of this table to make the calculation is illustrated by the following example:

Using the wind machine from the previous examples.

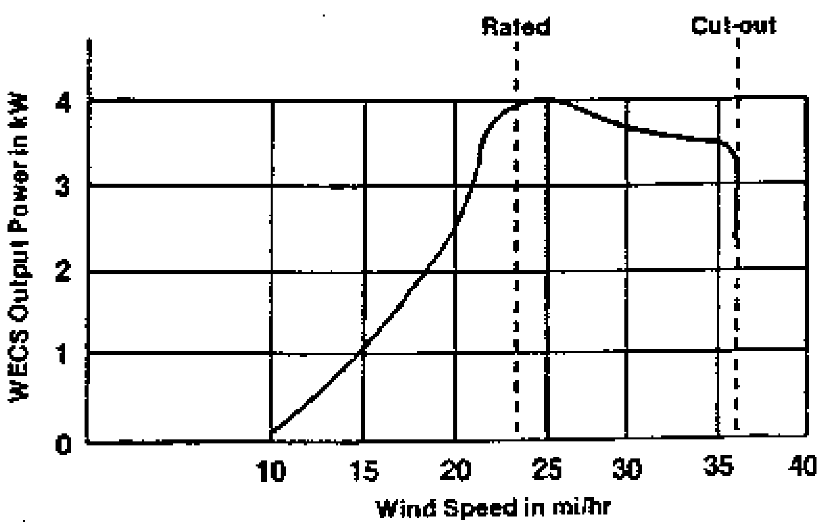
Cut-in wind speed = 10 mph

Rated wind speed = 24 mph

Average annual wind speed = 12.5 mi/hr @ 10 m (32.8 ft.)

Corrected to 60 ft. = 13.6 mi/hr

Figure 25. Hypothetical WECS Output vs Wind Speed.



From Table 9:

Average wind speed = 13 mi/hr
Cut-in wind speed = 10 mi/hr
Rated wind speed = 24 mi/hr
Annual power output = 1560 kWh
Average wind speed = 14 mi/hr
Cut-in wind speed = 10 mi/hr
Rated wind speed = 24 mi/hr
Annual power output = 1,890 kWh

Annual power output@13.6 mi/hr = [1560 + 0.60 (1890-1560)]4 = 7,032.00

Considering the complexities of the calculations, these values compare relatively well with each other. The differences are caused by the fact the actual WECS curve isn't exactly constant between rated and cut-out velocities, and some uncertainties exist about how wind speed varies with height. The answers are close enough for either to be used.

Table 9 can be used to analyze a wind machine at any site if the average wind speed can be estimated and the WECS power curve has a smooth shape between cut-in and rated velocity, as well as a reasonably constant output above its rated velocity.

All of the preceding methods give the average annual WECS output. In any given year, the actual output could be considerably different, since the average wind speed that year could vary considerably from the long-term average wind speed.

WORKSHEET 1

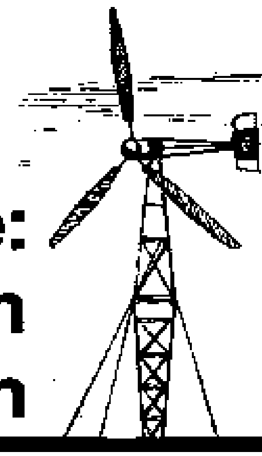
Complete Line 7 of Worksheet 1 by selecting a machine available to you, or one for which you have information, and estimating its annual electrical production from Worksheet 2 or Table 9.

Table 7. Hypothetical Annual Power Output (WECS at 60 ft. on clear level site, Fargo, ND)

Wind M/S	Speed Mi/Hr	Hours of Wind	WECS Power KW	Energy KWH
Calm	Calm	-	-	-
1.12	2.5	18	-	-
2.24	5.0	753	-	-
3.36	7.5	1340	-	-
4.48	10.0	1419	0.10	142
5.60	12.5	1279	0.56	716
6.72	15.0	1016	1.08	1097
7.84	17.5	867	1.70	1474
8.96	20.0	710	2.50	1775
10.08	22.6	490	3.90	1911
11.20	25.0	263	4.00	1052
12.32	27.6	114	3.9	445
13.44	30.1	79	3.7	292
14.50	32.6	53	3.6	191
15.68	35.1	17	3.5	60
16.80	37.6	9	-	-
17.92	40.1	0	-	-
19.04	42.6	0	-	-
20.16	45.1	0	-	-
21.28	47.6	0	-	-
22.40	50.1	0	-	-
			Total	9155 KWH

The energy estimate from Table 9 is for a 1-kW machine, so remember to multiply by the power rating of your selected machine to get proper annual kWh output. You may wish to try out on paper several different machines to see what power production to expect on your site or sites.

Chapter Five: Machine Selection and Economic Evaluation



Once a site's wind potential has been determined, the next step is sizing and selecting a WECS machine. Once you've accomplished this, you're in a position to evaluate the economics of the whole venture — site, machine and output.

This chapter offers information and techniques for these last two areas of concern: sizing a WECS and determining economic value.

Sizing the WECS

The optimum wind machine size depends upon a combination of the site's wind potential, the amount of energy used at the residence or business where it's installed and the applicable utility rate structure.

For most customers, electrical use varies with time; WECS output will also vary with time. This situation compounds the selection process and requires that purely economic criteria be discussed first.

Cost Economy

A WECS economic value is directly related to the price of other electrical power and, for those WECS owners connected to the utility grid, the buy-back rate paid by the utility for the WECS-produced electricity unused at its site.

There will be times when the WECS output is high and customer use low, such that energy will be stored on-site or "returned" to the utility. Conversely, there will be times when WECS output is low (zero during maintenance and periods of low or extra-high wind speeds) and user demand high, such that electricity is demanded from storage in the stand-alone installation, or from the utility in the parallel installation.

For the stand-alone case, the WECS' size is influenced by the cost of back-up power, the machine and fuel cost of another generator and, more particularly, the size and cost of storage batteries.

Buy-Back Rates

In North Dakota, the electric utilities must buy back electricity produced by a WECS. At the present time, there are three possible buy-back policies available to the parallel WECS.

The utility may pay for the WECS electricity at (1) less than the rate the customer ordinarily pays for electricity from the utility, (2) at the same rate the customer pays or (3) at a higher rate than the customer pays.

The lower-than-retail rate is presently the case for all North Dakota utilities. This is because the Federal Public Utilities Regulatory Policy Act

(PURPA) of 1978 stipulates public utilities must accept power from small parallel electrical energy producers (wind, hydro and solar) and buy it at the utility's avoided cost.

The avoided cost is defined as "the incremental costs to an electric utility of electric energy or capacity or both which, but for the purchase from the qualifying facility or qualifying facilities, such utility would generate itself or purchase from another source."

In practical terms this means utilities must buy electricity from WECS owners at a rate which reflects the fuel costs avoided, plus the cost of any new plant and equipment (capacity) avoided which would be needed to burn that fuel.

However, some North Dakota utilities presently have excess generating capacity and won't, therefore, be avoiding new capacity costs until 1985 or 1990. In these cases, electricity purchased from a WECS owner will only reflect the avoided fuel cost.

Most utilities distinguish between small power production facilities providing electricity on a "dependable" basis and those supplying electricity on an "occasional" basis.

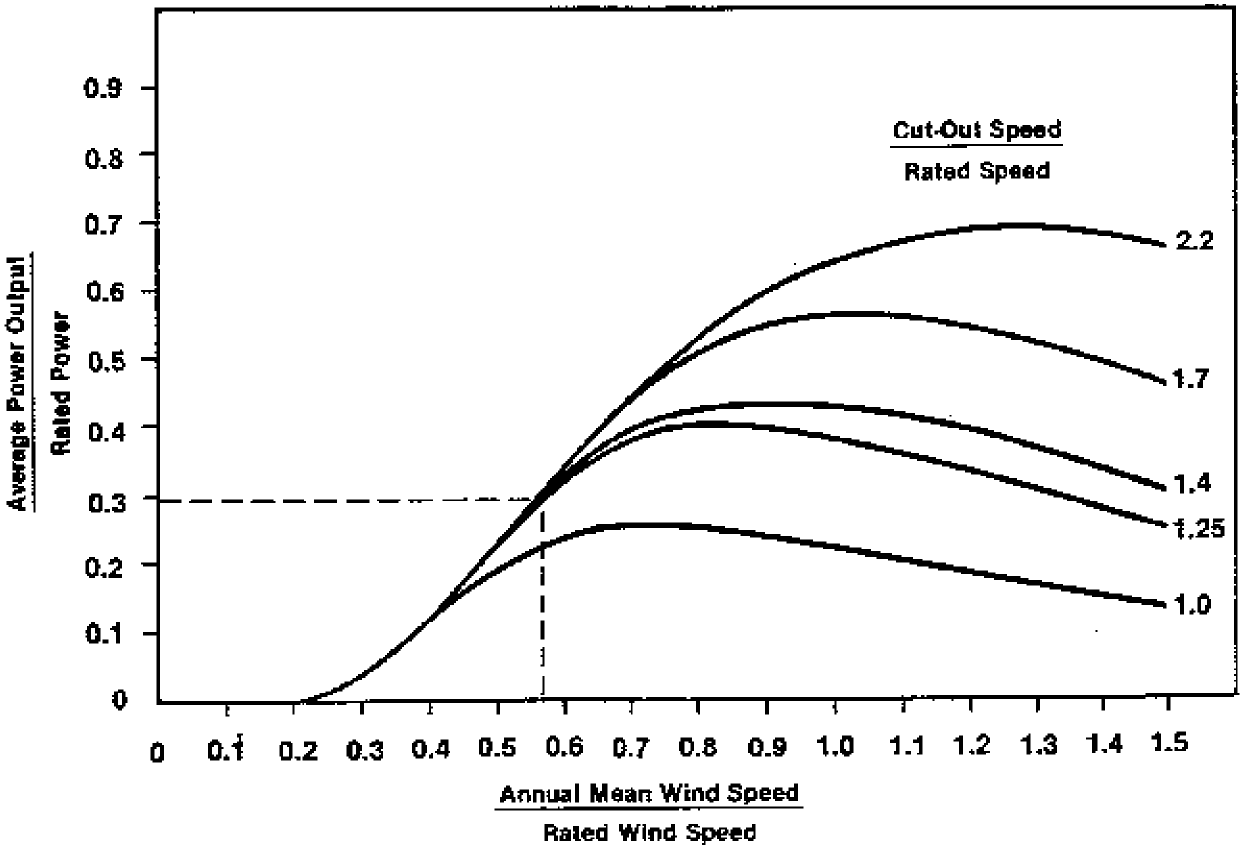
Higher rates are paid for dependable power, of course, but it must generally be delivered at a minimum of 65 percent capacity factor during the on-peak period in each month. This provision almost certainly excludes WECS facilities from "dependable" service contracts with utilities.

The lower-than-retail buy-back rate structure is implemented by installing two meters at the WECS site. Each meter is modified (detented) so it can only turn one direction. One meter measures elec-

Table 8. Wind Velocity Frequency, Selected Locations at 60 Ft. (number of hours at given speed)

Wind Speed M/S	Wind Speed Mi/Hr	Bismarck Hrs.	Dickinson Hrs.	Fargo Hrs.	Grand Forks Hrs.	Jamestown Hrs.	Minot Hrs.	Pembina Hrs.	Williston Hrs.
Calm	Calm	911	254	307	587	158	263	53	674
1.12	2.5	17	35	18	394	438	9	114	9
2.24	5.0	1314	324	753	1121	1183	289	858	955
3.36	7.5	1410	885	1340	1331	876	1156	876	1638
4.48	10.0	1323	1147	1419	1244	981	1585	990	1483
5.60	12.5	1016	1384	1279	1104	1603	1428	1699	1156
6.72	15.0	745	1051	1016	893	674	972	858	867
7.84	17.5	666	911	867	701	657	894	762	692
8.96	20.0	534	1051	710	561	569	894	920	631
10.08	22.6	412	666	490	333	613	753	447	333
11.20	25.0	201	438	263	219	289	289	342	166
12.32	27.6	79	184	114	105	219	79	280	70
13.44	30.1	52	140	79	70	228	52	272	44
14.50	32.6	35	114	53	53	114	52	114	35
15.68	35.1	17	70	17	17	61	18	79	9
16.80	37.6	9	44	9	9	53	9	52	9
17.92	40.1	0	26	0	9	17	0	18	0
19.04	42.6	0	17	0	9	9	0	18	0
20.16	45.1	0	9	0	0	9	0	9	0
21.28	47.6	0	9	0	0	9	0	9	0
22.40	50.1	0	9	0	0	0	0	0	0
23.5-28	52.6-62.6	0	9	0	0	9	0	0	0
29.1-33.6	65.1-75.2	0	0	0	0	0	0	0	0

Figure 26. Estimate of Expected Average Power Output for Wind Turbines.



tricity delivered by the utility and the other electricity returned. (Some utilities limit the amount of electricity they'll buy back from the parallel WECS system owner).

At the time of this writing, most North Dakota Utilities pay only 1-2 cents/kWh for occasional power delivered by a WECS. With lower-than-retail rates like these, a consumer generally doesn't want to purchase a large WECS which will return a significant amount of energy to the utility, since little credit will be received.

A retail-buy-back rate results in the WECS owner paying the utility for the net electrical energy used each month (sometimes called net energy billing). A single meter is used, and when energy is returned to the utility, the meter dials turn backwards. The effect — the utility buys back energy at the same rate it sells it.

Although this buy-back policy has been discussed by state WECS supporters, no North Dakota utility has adopted such a rate structure. But, even if a retail-buy-back or net energy billing policy comes into effect, you should select your WECS to produce no more than the average amount of energy used each month.

With a higher-than-retail rate structure, a larger wind-generator supplying more than just the energy needed at the WECS site may be economically feasible.

Presently, however, no state utility avoids fuel and capacity costs at a higher-than-retail rate when connecting to a WECS, and unless existing generating facilities are pushed to their capacity limits and utilities forced to build more expensive generating plants (possibly in the 1990s), none probably will.

Obviously, the rate structure affects significantly the size of the WECS to be installed. If a

Table 9. Annual Output from 1 kW WECS (adjusted for down time) (average wind-speed and cut-in speed in miles per hour) (cut-out speed 35 MPH)

Average Wind Speed	Cut-in Wind Speed	WECS Rated Wind Speed												
		18	19	20	21	22	23	24	25	26	27	28	29	30
11 mi/hr	7	2200	2000	1810	1650	1600	1370	1250	1150	.	.	.	.	.
	8	2050	1850	1680	1520	1380	1260	1150	1050	984	.	.	.	.
	9	1880	1700	1530	1380	1250	1140	1030	945	866	797	.	.	.
	10	.	.	1380	1240	1120	1020	920	840	770	700	650	.	.
	11	.	.	.	.	990	890	810	730	670	610	560	520	480
	12	.	.	.	.	.	780	700	630	570	520	480	440	410
12 mi/hr	7	2630	2410	2210	2020	1850	1700	1560	1440	.	.	.	.	.
	8	2480	2270	2080	1900	1740	1590	1460	1340	1230	.	.	.	.
	9	2330	2120	1940	1760	1610	1470	1350	1230	1130	1040	.	.	.
	10	.	.	1790	1620	1480	1350	1230	1120	1030	950	870	.	.
	11	.	.	.	.	1340	1220	1110	1010	920	850	780	720	670
	12	.	.	.	.	.	1090	990	900	820	750	690	630	580
13 mi/hr	7	3030	2810	2600	2400	2210	2040	1890	1750	.	.	.	.	.
	8	2900	2680	2470	2280	2100	1940	1790	1650	1520	.	.	.	.
	9	2750	2540	2340	2150	1980	1820	1670	1540	1420	1320	.	.	.
	10	.	.	2200	2010	1850	1970	1560	14030	1320	1220	1120	.	.
	11	.	.	.	.	1710	1570	1440	1020	1210	1110	1030	950	880
	12	.	.	.	.	.	1440	1310	1200	1100	1010	930	860	780
14 mi/hr	7	3400	3170	2980	2750	2580	2380	2210	2060	.	.	.	.	.
	8	3270	3050	2840	2640	2460	2280	2110	1960	1820	.	.	.	.
	9	3130	2920	2700	2520	2340	2170	2010	1860	1720	1600	.	.	.
	10	.	.	2580	2390	2210	2050	1890	1750	1620	1500	1390	.	.
	11	.	.	.	.	2080	1920	1770	1630	1510	1380	1290	1200	1110
	12	.	.	.	.	.	1790	1650	1520	1400	1290	1190	1100	1020
15 mi/hr	7	3720	3500	3290	3080	2890	2700	2520	2360	.	.	.	.	.
	8	3600	3390	3180	2960	2790	2600	2430	2270	2110	.	.	.	.
	9	3480	3270	3080	2880	2680	2500	2330	2170	2020	1860	.	.	.
	10	.	.	2930	2740	2560	2390	2220	2080	1920	1760	1660	.	.
	11	.	.	.	.	2430	2280	2100	1950	1810	1660	1560	1450	1360
	12	.	.	.	.	.	2130	1980	1830	1700	1570	1460	1360	1260

Worksheet 2
Annual WECS Energy Output
(from wind velocity frequency and from machine power output)

		WECS #1		WECS #2		WECS #3	
Wind Speed mi/hr	Hours of Wind	Output Power kW	Energy kWh	Output Power kW	Energy kWh	Output Power kW	Energy kWh
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
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32							
33							
34							
35							
36							
37							
38							
39							
40							
		Total Energy					
		Correction Factor					
		Expected Output					

net energy rate is in effect, and the utility won't pay for more than it sells, a WECS generating a little less energy than the monthly use should be installed.

On the other hand, if the utilities' avoided costs escalate to levels above retail rates, then the consumer might consider installing as large a wind machine as is appropriate to the site or investment desired; then the choice can be made with little consideration for the amount of energy used at the site.

But, if the buy-back rate is at the lower-than-retail rate — as is the case for all present state utilities — then the WECS should be sized so that most of its output is used directly and little returned to the utility.

By examining the rate structure, a consumer can begin to determine (make an educated guess) how it impacts WECS sizing in his or her situation.

Table 10. On-Site WECS Electrical Use Factor, Residential, Non-electric Space Heating (in percent WECS annual output)

Annual Output of WECS in kWh	Average Monthly Use in kWh				
	500	750	1000	1500	2000
2000	62.5	83.9	97.0	100.0	100.0
4000	42.0	59.5	75.0	96.5	99.9
6000	31.3	47.8	61.0	83.2	96.0
10000	20.4	34.0	45.9	64.3	78.0
15000	14.3	24.8	34.5	50.2	62.6
20000	11.0	19.5	27.4	40.7	51.5

Table 11. On-Site WECS electrical Use Factor, Residential, Electric Space Heating (in percent WECS annual output)

Annual Output of WECS in kWh	Average Monthly Use in kWh			
	1500	2000	2500	3000
6000	58.7	72.9	97.1	99.3
10000	49.3	62.1	83.6	91.9
15000	38.6	58.2	73.5	80.9
20000	31.6	45.1	64.3	71.5
30000	23.1	33.6	49.7	56.4

Table 12. On-Site WECS Electrical Use Factor, Commercial, and Industrial (in percent WECS annual output, 8 a.m. to 5 p.m. business day)

Annual Output of WECS in kWh	Average Monthly Use in kWh				
	4000	6000	8000	10000	12000
25000	65.9	74.9	80.3	84.7	88.5
50000	43.9	57.0	66.0	71.3	74.9
75000	32.2	43.9	53.5	60.4	65.9
100000	25.3	35.3	44.0	51.5	57.1
150000	17.7	25.3	32.2	38.3	43.9
200000	13.6	19.6	25.3	30.6	35.3

Electrical Use Factor

The following three tables present estimates of the proportion of WECS-generated electricity that would be directly used on-site (and the remainder being returned to the utility or stored): Table 10 presents information for residences with non-electric space heating, Table 11 gives data for all-electric residences and Table 12 estimates business utilization factors.

The percentage shown is a function of monthly energy demand and the wind machine's energy output. These tables can be used to help determine the optimum WECS size for a given buy-back rate. The tables are estimates made from assumptions about how house electrical-demand and wind-speed varies during the day and year. For example, suppose a WECS expected to generate 6,000 kWh per year is being considered for a gas-heated residence using an average of 1,000 kWh per month.

In such a situation, 61 percent of the energy will likely be used directly and 39 percent sold to the utility.

Table 12 assumes most electricity is used by a business between 8 a.m. and 5 p.m. An individual business may have different hours, so the table may not apply.

Future data and experience may improve these tables. But, for the present, they provide the most reasonable estimates available.

Widespread use of load management techniques may change the amount of electricity purchased from and returned to the utility. If the WECS user delays certain tasks, such as clothes drying and air conditioning, until a time when the WECS output is high, the electrical use factor can probably be improved.

WORKSHEET 1

Complete Lines 8 and 9 by selecting an appropriate electrical use factor from Table 10, 11 or 12, and multiplying to determine the likely on-site utilization and that available for sale to the utility.

In the stand-alone case, this split gives an estimate of the energy being utilized directly and that going to storage. Doing this for several machines will illustrate the range of potentials.

Value of the WECS

The next step is estimating the savings on the monthly electricity bill when the WECS is used.

In most cases, the savings are determined from the unpurchased electrical energy (i.e. "saved" by your investment in your own machine), although in some cases all the WECS-produced energy may be sold directly to the utility, independently of what's being purchased for home use.

Care must be taken to determine exactly what energy is being displaced. For example, suppose the rate structure for a residence served by an electric utility is:

$3 service charge each month
5 cents/kWh for the first 800 kwh
4 cents/kWh for all usage after the first 800 kwh
(1.5 cents/kWh for fuel cost)

(Ask your local utility office for these rates; they're the rules determining how you'll be billed for electricity. They're established by the utility and for all regulated utilities and must be approved by the North Dakota Public Service Commission.)

Further suppose the residence uses about 1,000 kWh per month, and the wind machine, as in the earlier example, will supply 6,000 kWh per year.

The monthly average WECS output will be 500 kWh (6,000 kWh ÷ 12) and, from the values in Table 10, 61 percent, or 305 kWh/month will be used directly. Thirty-nine percent, or 195 kWh, will be returned to the utility each month.

First, consider the utility bill without the WECS. Then consider the savings in the three buy-back situations.

Without WECS

In this example, the electrical cost without a WECS is the service charge, plus the cost for the first 800 kWh at the base rate, plus the cost for the last 200 kWh at the lower rate:

Service charge	$ 3.00
First 800 kWh: 800 @ 5 cents	40.00
Over 800 kWh: 200 @ 4 cents	8.00
Monthly electric bill	$51.00

Low Buy-Back

Assume the buy-back rate is set at the utility's fuel cost, or 1.5 cents/kWh in this example. Of the 305 kWh/month used directly, 200 kwh displaced the 4 cents/kWh electricity and the remainder (105 kwh) cut into the 5 cents/kWh electricity. The 1.5 cents/kWh rate applies to the 195 kWh returned to the utility. Or:

4 cents/kWh displaced: 200 @ 4 cents	$ 8.00
5 cents/kWh displaced: 150 @ 5 cents	5.25
Sold to utility: 195 @ 1.5 cents	2.93
Savings	$16.18

And the utility bill will be:

Monthly electric bill without WECS	$51.00
Savings	16.18
Electric bill	$34.82

Retail Buy-Back

With retail buy-back, one meter indicates a net 500 kWh of utility electricity has been used and the actual bill will be the service charge, plus use, or $\$3 + 500 \times 5$ cents = $28.

Since the WECS average output is less than the average consumption, and its output is estimated to be 500 kWh, the savings are:

4 cents/kWh displaced 200 @ 4 cents	$ 8.00
5 cents/kWh displaced 300 @ 5 cents	15.00
Savings	$23.00

And the utility bill will be:

Monthly electric bill without WECS	$51.00
Savings	23.00
Electric bill	$28.00

Higher-Than-Retail Buy-Back

At the time this publication is released, higher-than-retail buy-back rates don't exist in North Dakota. But if, as an example, the buy-back rate was 7 cents/kWh, the savings in the same format as above would be:

4 cents/kWh displaced: 200 @ 4 cents	$ 8.00
5 cents/kWh displaced: 105 @ 5 cents	5.25
Sold to utility 195 @ 7 cents	13.65
Savings	$26.90

And the utility bill will be:

Monthly electric bill without WECS	$51.00
Savings	26.90
Electric bill	

It's more likely the WECS owner would sell all the WECS-generated electricity back to the utility at the higher-than-retail rate and buy all site-used electricity from the utility at the normal retail rate. Or:

Monthly electric bill without WECS	$51.00
Sold to utility 500 @ 7 cents	35.00
Electric bill	$16.00

This example is based on one particular wind machine's output at a specific site, with a typical set of rates given.

Not surprisingly, the best savings occur in the situation where the buy-back rates are higher than the retail rates. In fact, if the high buy-back rate's in effect, an even larger WECS might be evaluated for its potential at the site.

These three examples illustrate the significant way the WECS' economic value is influenced by electric utility rates. Obviously, future rates will have a profound impact on a WECS' economic value.

Your own savings calculations may be more complicated than the above example.

For some state utilities, rates vary during the year. Summer rates are typically higher than winter rates, so calculations will need to be made for each rate and an average monthly savings determined.

In addition, the amount of electricity usage will vary with the season, complicating the calculation of average monthly savings. As a result, it will probably be impossible to calculate the savings obtained exactly. However, using the rate structure, the WECS energy output and a little common sense, a reasonable estimate should be possible.

There are other features of rate structures that may be encountered when the monthly savings is being estimated.

One is the fuel-charge-adjustment, an extra cost per kWh passed on to the consumer, dependent upon the cost of fuel being burned to produce electricity. This adjustment typically varies monthly, but the utility will usually tell you the average surcharge, which can then be used in the monthly costs/savings. Taxes and other surcharges may also raise the cost per kWh, and must be included in your calculations.

Businesses, and some residences, may also have a "demand charge" as part of their monthly bill. The demand charge is related to the peak monthly (or yearly) demand. The WECS owner should read the utility's PURPA policy statement to find out if the WECS will affect demand billing.

WORKSHEET 1

Now continue Worksheet 1 by identifying the necessary rates appropriate to Line 13. Consider Line 9 and the likely allocation of kWh at different rates, then multiply out each rate and add to find the monthly costs and savings for each prospective machine at each site.

Future Value of the WECS

Now you're ready for the difficult part — estimating how much to pay for a wind machine.

Will it be a wise investment? Will it make as much, or more, money than some other reasonable investment?

Up to this point, the estimates, even if uncertain, are based on things that can be measured (wind-speed, tower height, output curves) or for which there are answers (your current utility rate). Now, however, you must deal with such questions as future electricity prices and inflation rates.

While these are difficult questions, you aren't alone in dealing with this problem. Businesses, utilities and government agencies are all struggling with these energy planning questions, compounded by the global nature and increasing complexity of energy systems, and by the uncertain change rates in consumption, production and prices.

Yet, despite these difficulties, you'll have to make some estimates to make a decision.

In addition to the above cautions, additional issues have to be considered in the analysis of WECS value.

The complete financial picture depends not only on the future electricity costs, but also on the installed WECS system cost, (including incidental costs like interconnection equipment and liability insurance policies), tax credits obtained by the WECS installation (and, in turn, the incremental federal and state income tax bracket of the owner), interest rates for borrowing money to buy the WECS (even if you borrow from yourself, it's a factor), the amount of required WECS maintenance and the WECS lifetime (or amount of time you want it to take for a return on your investment).

For business use, the method of depreciation is also a consideration.

All these factors make the economic picture rather complicated, and a complete explanation of all possible economic calculation won't be given here.

Instead, a technique is presented to help you identify future WECS values. The technique gives a very rough estimate of WECS value.

Rough Cost Estimate

Only for residential users, the rough cost method is simple, but not always accurate. To estimate a WECS installation value, simply take the monthly savings and multiply by the number of months you expect to use the WECS to get the total savings.

Then, if you're considering buying a WECS costing $5,000 or less, multiply the total savings by 2.5.

The multiplier reflects the tax credits you'll receive. If the total savings times 2.5 is greater than the WECS cost, the investment is worthwhile.

If you're considering a WECS costing between $5,000-$10,000, multiply the total savings by 2.0.

This simple method will give you a rough estimate of the amount you can pay for a WECS, up to about $10,000. For a WECS costing more than $10,000 simply add $5,000 to the total savings.

Several examples follow that use this method:

Consider the WECS saving $25 per month and you wish to pay for itself in seven years (84 months). Is this $5,000 WECS a good investment?

To follow the rough estimation procedure, take $25 × 84 = $2,100 and multiply by 2.5 to get a "rough cost" estimate of $5,250. Its value exceeds its costs by about $250, so the investment looks reasonable.

As second example, consider a machine to be used for 15 years (180 months).

In this instance, $25 × 180 = $4,500, multiplied by 2 (since the cost is in excess of $5,000). Then, 2 × $4,500 = $9,000 could be paid for the machine.

For our third example,

consider a WECS saving $75 per month that must pay for itself in five years (60 months).

In this case, $75 × 60 = $4,500, multiplied by 2 gives $9,000 as the estimate of its value.

Finally, consider a WECS saving $100 per month for 15 years. The savings are $100 × 180 = $18,000. Adding $5,000 (for WECS costing more than $10,000) gives $23,000.

You should determine a cost/value estimate for each machine at each site, in order to compare relative values.

These analysis procedures can be very useful, as long as their limitations are remembered. In all cases, more precise estimates of power production may be calculated when more precise wind-speed data becomes available. Remember, however, that an "average" year never occurs.

When new utility rates are determined, a newer and more realistic estimate can be made of electrical costs and savings. But, the WECS value will always be a moving target, and decisions to act must be made. Hopefully, the procedures and techniques of this chapter will be informative enough to aid you in decisions about alternative energy investments.

Chapter Six: Installation and Operation

If you've followed the discussion and rationale of the preceding chapters, and (especially) completed Worksheet 1, then you're ready to deal with a few final sets of hurdles before installing a wind machine.

Locale

While earlier chapters dealt with locale from a wind environment and technical perspective, locale here relates to social and political considerations.

What are the regulations limiting WECS installations and/or affecting the installed cost? Answers here vary greatly across the state.

You can expect development issues in, say, rural Slope County to differ from those in the metropolitan Fargo area. But, since some issues vary even within counties, each site must be considered on its own. Two general areas are covered here: land use regulations and building code regulations.

Land Use Regulations

Private and public land use regulations may affect WECS installations.

Private regulations include deed restrictions and covenants. Read your deed and check out any convenants applying to your land.

This is most likely to be a problem in a new urban residential subdivisions, or even industrial parks. And, while some restrictions can be amended, others are immutable, leaving you the single recourse of finding another site.

Zoning

Zoning is the principal public land-use regulation to be considered. A local zoning ordinance may limit tower height, specify the tower's setback from the property line be greater than the tower height or even specify the setback be equal to the maximum distance a rotor blade could be thrown from the WECS.

Therefore, talk to the zoning administrator with jurisdiction over your site to determine the particular zoning provisions that apply.

Zoning regulations aren't uniform from one jurisdiction to another, and requirements vary from one zone to another within any given ordinance.

Since you usually want to mount a WECS as high as you can afford, height restrictions are a likely zoning limitation for a successful installation.

Overcoming height and other restrictions varies greatly from one jurisdiction to another. In some cases, a simple request for a special permit may be all that's required.

In other cases, a zoning change, a change in the ordinance text or a variance may be necessary — each has a different procedure, with a different chance of success in any given situation.

Building Codes

Some potential WECS sites, particularly in urban areas, are subject to building code regulations. Since long-term safety considerations are at the base of most items in a building code, it should always be followed.

In fact, all appropriate safety elements should be followed, even if not required by a local jurisdiction.

Most codes allow owners to do most work, subject to inspection. If you don't do your own installation, some building code items may increase the installation cost — such as requiring a licensed electrician to make certain connections, install meters, etc. Rarely will this additional cost be the single make-or-break element in your decision to install a WECS.

Insurance

One necessary operations element is insurance. There are two types of insurance a WECS owner should be interested in: liability insurance, in case the WECS causes any damage, and insurance for the wind machine itself, in case it's damaged or stolen.

Since there aren't a large number of WECS presently operating in the state, insurance companies have limited experience covering WECS, and their policies differ. It appears, therefore, that when you wish to insure your WECS, it's best to shop around, just as you do when shopping for other products and services.

A 1982 inquiry into windmachine insurance in Fargo drew the following responses: With one company, a residential site WECS would be covered under the existing household policy as a rider at $30,000. The liability could be covered by the existing policy or an umbrella policy that would take care of liability over and above the regular liability policy.

One company writing policies for farmers indicated that they would insure the WECS as if it were another building on the farm.

No information was gathered on insurance for the commercial use WECS; it is expected that the findings would be similar to that for residential policies, again there will probably be some variation between one company and another. A prospective WECS owner should contact insurance companies in their area to determine policies and prices. It appears that some comparison shopping would be in order, and that significantly different rates for essentially the same coverage can be obtained.

APPENDIX A

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APPENDIX B

North Dakota Tax Incentives

The 1981 Legislature passed a law allowing a tax credit for the cost of a geothermal, solar or wind energy device installed or on property owned by a North Dakota taxpayer.

The credit is limited to 5 percent for three years of the actual cost of acquisition and installation of the geothermal, solar or wind energy device.

The three years in which the credit must be used are the year of installation and the two years immediately following.

If a geothermal, solar, or wind energy device is part of a system using other means of energy, only that portion of the total system directly attributable to the cost of the geothermal, solar or wind energy device can be included in determining the amount of the credit.

The cost of installation will not include costs of redesigning, remodelling, or otherwise altering the structure of a building in which a geothermal, solar or wind energy device is installed.

This credit is available to any taxpayer who installs within North Dakota a geothermal, solar, or wind energy device on or after January 1, 1981.

The 1981 Legislature approved an expanded property tax exemption for solar, wind or geothermal energy systems.

1. An exemption from property tax for a solar, wind, or geothermal energy system is valid for five years following the date of the system's installation.

2. Property exempted includes installations, machinery, and equipment of systems in new or existing buildings or structures, designed to provide heating or cooling or to produce electrical or mechanical power, or any combination of these, or to store any of these, by utilization of solar, wind or geothermal energy.

3. If the solar, wind or geothermal energy device is part of a system using other means of energy, only that portion of the total system directly attributable to solar, wind or geothermal energy will be exempt.

Those who wish to apply for this exemption should contact their local assessor or their county director of tax equilization.